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FIGS. 1–9, MARCH, 1961

COMPOSITION, GRAIN SIZE, ROUNDNESS, AND SPHERICITY OF THE POTSDAM SANDSTONE (CAMBRIAN) IN NORTHEASTERN NEW YORK[1]

DONALD R. WIESNET
U. S. Geological Survey, Washington, D. C.

ABSTRACT

The Potsdam Sandstone of Late Cambrian age crops out along the north, east, and southeast borders of the Adirondack Mountains in northeastern New York State. It has generally been described as an orthoquartzite. In the Mooers area, however, the Potsdam is mainly a subarkose or arkose.

Detailed analysis of 10 thin sections of the Potsdam Sandstone from the Mooers Quadrangle provide data for grain-count composition, median grain size, cumulative size curves for individiaul samples, mean grain size, coefficient of sorting, roundness, and sphericity. The examination of 25 additional thin sections provided data for a lithofacies map.

In the Mooers area, the Potsdam can be distinguished from the sandstone in the overlying Theresa Dolomite, which, unlike the Potsdam, contains no zircon, very little feldspar, and very well rounded quartz grains. Mean grain roundness in the Potsdam ranges from 0.4 to 0.5; sphericity ranges from 0.73 to 0.79. The relation of roundness to sphericity is similar to that reported in other published studies. The median size decreases and sphericity increases to the north, away from outcropping Precambrian rocks. Sorting is best and median grain size smallest where the beds dip least, suggesting that the dip is probably primary. Sedimentary analysis by thin-section techniques gives abundant, fairly reliable quantitative data for sedimentary studies.

INTRODUCTION

Specific information is lacking on the size and shape of grains and on the composition of the Potsdam Sandstone of Late Cambrian age, although it was one of the first formations named in the United States (Emmons, 1838). The Potsdam Sandstone has been described in general terms, but few quantitative data have been published except by Colony (1919). Pettijohn (1957) lists the Potsdam as a true orthoquartzite. Fisher (1956, p. 338), in a review of the Cambrian of New York, commented on its ". . . exceptionally low feldspar content." The results of the present study show, however, that feldspar is quite abundant in the Potsdam in the Mooers Quadrangle.

In the course of routine examination of thin sections of the Potsdam Sandstone from northeastern New York, an unexpectedly large amount of feldspar was noted. This paper is the outgrowth of an attempt to delineate the arkosic and subarkosic facies of the Potsdam in the Mooers Quadrangle, New York (fig. 1), using thin-section techniques. Several factors affect the mapping of the Potsdam Sandstone: outcrops are generally scarce; mappable zones within the formation are absent owing to abundant, large-scale crossbedding; fossils are rare, local, and fragmental; and the upper boundary is poorly defined.

This study was a "pilot" operation to determine whether stratigraphic zones or lithofacies could be mapped by detailed sedimentary analysis. Although the data are restricted to one area and cannot be applied to the formation as a whole, they represent quantitative information that may be useful to workers in nearby areas and to those studying the petrology of feldspar-rich sedimentary rocks. If this paper stimulates further petrologic and stratigraphic work on the Potsdam Sandstone, it will have served its purpose. I should like to acknowledge the help of W. C. Krumbein, who pointed out the pertinence of Friedman's (1958) paper on thin-section size analysis.

GEOLOGY OF THE AREA STUDIED

The Potsdam Sandstone crops out along the north, east, and southeast borders of the Adirondack Mountains. It is the basal sedimentary deposit on the uneven surface of

[1] Publication authorized by the Director, U. S. Geological Survey. Manuscript received February 24, 1960.

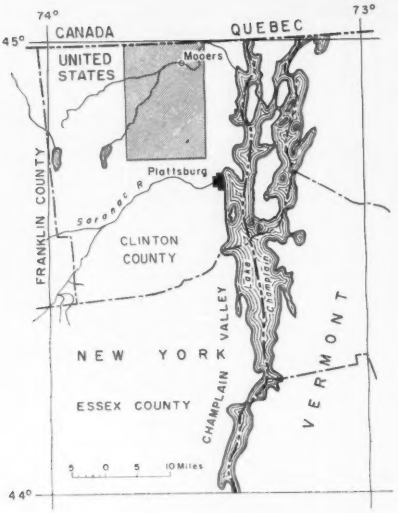

FIG. 1.—Index map showing location of the Mooers Quadrangle.

the Precambrian rocks of the Adirondack Dome. The dome is connected to the Canadian Shield by the Frontenac Axis, a narrow isthmus of northwest-trending Precambrian rock about 135 miles west-southwest of Mooers. The Potsdam increases in thickness away from the Adirondack Mountains and is presumed to be as much as 1750 ft thick in the area studied. It grades upward into the Theresa Dolomite, which is an alternating series of orthoquartzite and dolomite beds. The similarity between the orthoquartzite of the Potsdam and Theresa makes it difficult to map the boundary between the two formations. The Potsdam is diverse lithologically and contains beds that range from a red shale and siltstone unit to conglomerate; in the samples collected in the Mooers Quadrangle it ranges compositionally from arkose to orthoquartzite. On the basis of the 35 thin sections studied, the Potsdam Sandstone is chiefly a subarkose (feldspathic sandstone) and locally an arkose or orthoquartzite. The distribution of these rocks is shown on the lithofacies map (fig. 2). Crossbedding, which is common in the Potsdam, decreases in scale toward the top of the formation.

In this report the term "arkose" refers to a rock whose clastic constituents are at least 25 percent feldspar, the term subarkose refers to a rock containing 10 to 25 percent feldspar, and the term orthoquartzite refers to a rock containing less than 10 percent feldspar.

METHODS OF STUDY

The sedimentary analysis of a clastic rock is best accomplished by disaggregation and examination of the particles—the clastic material. Measurement of such parameters as particle size, roundness, sphericity, and mineral composition provide the main basis from which the environment of deposition may reasonably be inferred.

Disaggregation of the Potsdam is impossible: it is hard and tough and is cemented by a secondary growth of quartz (on quartz) and—less commonly—feldspar (on feldspar). For this reason the Potsdam Sandstone is best studied in thin section.

Krumbein's (1935) experimental research supplied the sedimentary petrologist for the first time with a method of approximating the average grain size of sedimentary rocks from thin sections. Krumbein (1941) later derived a method of determining roundness by visual comparison. In 1943 Rittenhouse provided a technique for measuring two dimensional sphericity. Chayes (1950) pointed out the bias in Krumbein's method of determining grain size, and Rosenfeld and Griffiths (1953) have evaluated the visual techniques for determining two-dimensional sphericity and roundness. In 1958 Friedman published a method of obtaining the sieve-size distribution from thin-section data.

Size Analysis

Photographs of the thin sections (×50) were made, and the diameters of 100 grains were measured directly from each 8×10-in photograph. The grains that were selected for analysis were intersected by straight-line traverses across the photo. Four or five traverses were made on each photo. The individual grain measurements were recalculated into phi units using a phi-millimeter scale (Page, 1955) and plotted as cumulative curves (fig. 3) from which the corrected sieve-size equivalents were obtained (Friedman, 1958). The average grain size in milli-

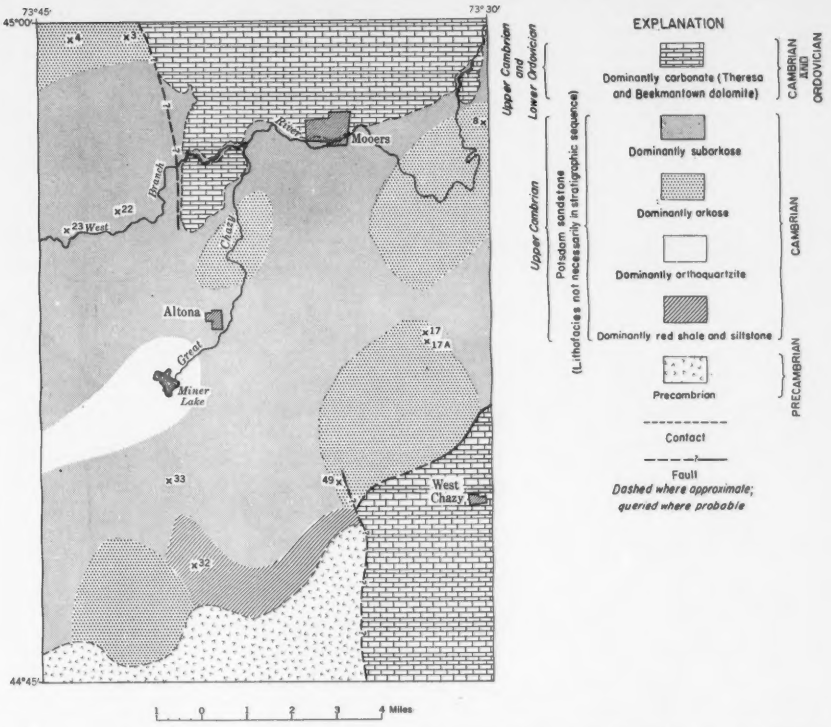

FIG. 2.—Generalized geologic map of the Mooers Quadrangle showing the lithofacies of the Potsdam Sandstone and the location of the samples analyzed in table 1.

meters was calculated from the thin-section measurements, as well as by Krumbein's (1935) method for comparison. These data are compared in table 1.

Roundness and Sphericity Determinations

The image of the 8×10-in enlargement used in the size analysis was projected with a Saltzman projector and was readily compared with roundness and sphericity charts (Krumbein, 1941; Rittenhouse, 1943). The Saltzman projector enabled the operator to enlarge or decrease the image size of the grain with a minimum loss of time. A transparent overlay numbering grid was left over the photograph so that each grain was permanently identified as to intercept, roundness, two-dimensional sphericity, and mineral composition. Repeated readings indicated an average reliability of about 0.1 in roundness values and less than 0.05 in two-dimensional sphericity values of the individual grains.

Composition

The grains were identified in thin section by using the petrographic microscope in conjunction with the enlarged photomicrograph to locate the exact grain.

Five chip samples of the Potsdam Sandstone from one locality (between loc. 22 and 23, fig. 2) were analyzed chemically by methods described by Shapiro and Brannock (1956).

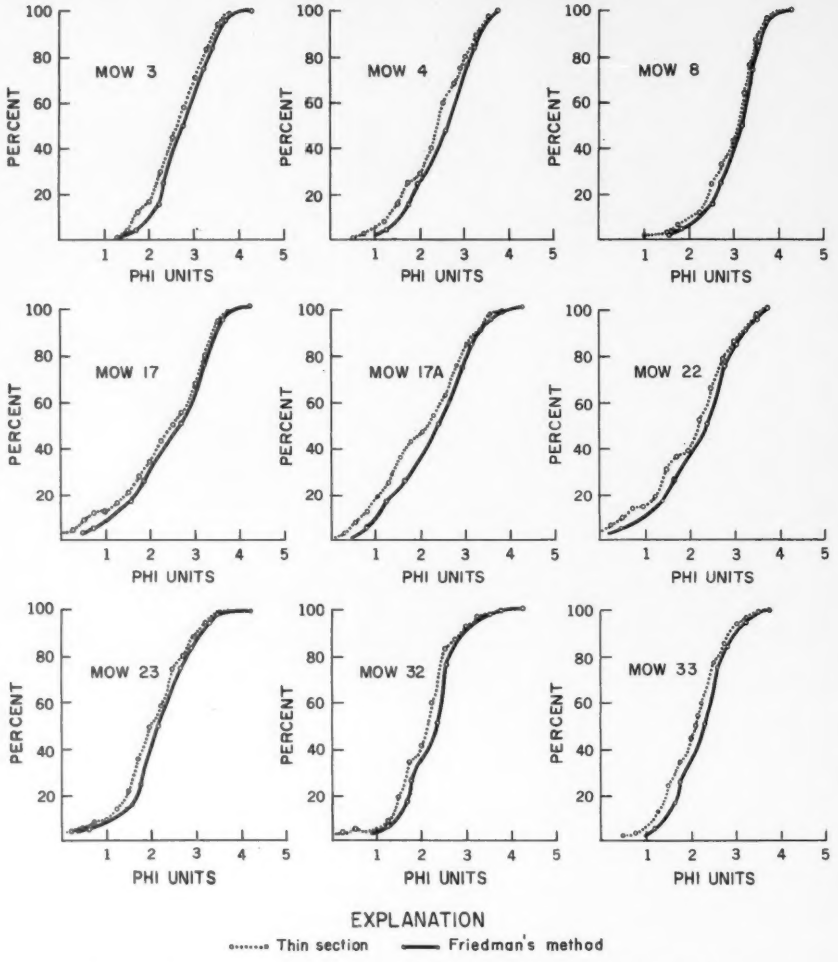

FIG. 3.—Cumulative frequency curves for thin-section and sieve-equivalent data.

RESULTS

Mineral Composition

The composition of the Potsdam in the Mooers Quadrangle is typically that of a subarkose (10–25 percent feldspar) and less commonly that of an arkose; orthoquartzite is rare (fig. 2). Zircon is present in almost every thin section of the Potsdam but nowhere does it amount to more than 1 percent of the sample.

The composition of two samples of the Potsdam as determined by grain-count analyses is compared in table 3 with Rosiwal analysis made of the same two samples.

The Rosiwal analyses traversed essentially the entire slide; the grain-count analyses took in only the portion of the slide

TABLE 1.—*Parameters of the Potsdam Sandstone*

Sample No.	Rock type	Median grain size (phi units)		Mean grain size (mm)[2]	S_o[3]		Grain-count composition			Roundness	Sphericity	Precambrian Dist. from (miles)
		Thin sect.	Sieve equiv.[1]		Thin sect.	Sieve equiv.	Qtz.	Feld.	Other			
MOW 3	arkose	2.50	2.70	.22	1.37	1.34	62	38	0	.5	.78	15.3
MOW 4	arkose	2.40	2.60	.28	1.46	1.36	71	28	1	.5	.77	15.6
MOW 8	arkose	3.05	3.15	.18	1.42	1.37	47	52	1	S.E.[4]	S.E.[4]	11.2
MOW 17	arkose	2.55	2.70	.32	1.65	1.41	59	39	2	.4	.75	5.2
MOW 17A	arkose	2.15	2.30	.38	1.68	1.57	71	25	4	.4	.74	5.2
MOW 22	subarkose	2.25	2.40	.37	1.52	1.44	74	24	2	.5	.79	10.5
MOW 23	subarkose	2.00	2.20	.37	1.15	1.02	74	18	8	.4	.77	10.5
MOW 32	arkose	2.10	2.30	.37	1.30	1.25	69	26	5	.4	.73	1.3
MOW 33	subarkose	2.10	2.30	.25	1.37	1.32	81	18	1	.4	.78	3.4
MOW 49[5]	arkose	2.30	2.50	.57	1.57	1.52	71	25	4	.4	.75	1.3

[1] After Friedman, 1958.
[2] After Krumbein, 1935.
[3] S_o = Coefficient of sorting.
[4] Because of secondary enlargement of grains this parameter could not be determined.
[5] Arkosic interbed in a terrane predominantly of red shale and siltstone.

that appeared in the photomicrograph.

Microline and an unidentified cloudy feldspar are equally abundant and together constitute an estimated 60 percent of the feldspar in the Potsdam. Plagioclase is relatively common in the east half of the Mooers Quadrangle but is rare in the west half. The perthitic-type feldspar seems to be restricted mainly to those areas near the Precambrian rocks.

Colony (1919) published a report on high-purity silica in the unconsolidated sandstones and sands of New York State. Although he noted that the Potsdam was rather feldspathic, his samples were highly selective, and his thin-section analyses showed the Potsdam to be relatively pure with little feldspar. He lists no analyses from the Mooers area, but his reference to the "quartzitic phase" of the Potsdam in the town of Mooers is believed to be to orthoquartzite beds in the overlying Theresa Dolomite. Gilbert (in Williams, Turner, and Gilbert, 1954, p. 317) shows a drawing of a thin section of the Potsdam Sandstone from Lake Champlain, N. Y., which consists of 85–90 percent quartz and 10–15 percent feldspar.

Twenty-five thin sections—not shown on table 1—were examined to draw the lithofacies map (fig. 2) in addition to the 10 thin sections analyzed in detail (table 1). The percentage of feldspar in the 25 additional thin sections was determined by visual comparison with thin sections of known percentage composition. Estimating the per-

TABLE 2.—*Chemical analysis of the Potsdam Sandstone compared to that of an average orthoquartzite and an average arkose (in percent)*

	Orthoquartzite[1]	Potsdam Sandstone[2]	Arkose[3]
SiO_2	93.16	92.6	76.37
TiO_2	0.03	0.24	0.41
Al_2O_3	1.28	3.52	10.63
Fe_2O_3 / FeO	0.43	0.44	3.34
MgO	0.07	0.04	0.23
CaO	3.12	0.06	1.30
Na_2O / K_2O	0.39	2.93	6.80
H_2O	0.65	0.17	0.83
CO_2	2.01	0.06	0.54
P_2O_5	—	0.02	0.21

[1] Average of 8 samples, Pettijohn, 1957, p. 298.
[2] Average of 5 samples; P. L. D. Elmore and K. E. White, analysts, Samples analyzed by methods described in U.S.G.S. Bull. 1036-C.
[3] Average of 5 samples, Pettijohn, 1957, p. 324.

TABLE 3.—*Comparison of grain-count and Rosiwal analyses*

	MOW 8		MOW 4	
	Grain-count (percent)	Rosiwal (percent)	Grain-count (percent)	Rosiwal (percent)
Quartz	47	44	71	70
Feldspar	52	56	28	29
Other	1	—	1	1
Total	100	100	100	100

centage of the feldspar was facilitated by its turbid or cloudy condition and its contrast to the clear quartz.

Of the 25 additional thin sections, 11 were subarkose (10 percent to 25 percent feldspar), nine were arkose (more than 25 percent feldspar), and five were orthoquartzite (less than 10 percent feldspar). Two of the five orthoquartzite samples were very close to the Theresa contact.

Six thin sections of sandstone from the Theresa Dolomite were also examined. All contained less than 1 percent feldspar; none contained detrital zircon. Feldspar grains were much smaller than the quartz. Three were dolomite-cemented quartz sandstone; three were orthoquartzite with traces of interstitial dolomite.

Chemical Composition

The data presented in table 2 compare the average chemical composition of five chip samples of Potsdam Sandstone, the average chemical composition of eight samples of orthoquartzite, and the average chemical composition of five samples of arkose. The feldspar shows up chiefly in the Na_2O-K_2O content. The Na_2O-K_2O content of the Potsdam is intermediate between that of the orthoquartzite and the arkose. Figures for other subarkoses are unknown to the author. The low CaO content confirms the absence of significant amounts of anorthite. The TiO_2 content may be attributed to ilmenite and (or) leucoxene.

Roundness and Sphericity

The mean roundness of nine samples of Potsdam Sandstone ranges from 0.4 to 0.5 (table 1). Separate determination of feldspar and quartz rounding failed to reveal significant differences (fig. 4).

In figure 5, roundness is plotted as a function of sphericity and the resultant graph is compared with previous studies by Pettijohn and Lundahl (1943) and Wadell (1935). The slope of the curve is probably a little too steep, as sphericity values determined from thin sections are normally higher than those from whole grains which can be oriented properly. Rosenfeld and Griffiths (1953, p. 553) feel that this sympathetic relationship arises from psychological bias on the part of the operator.

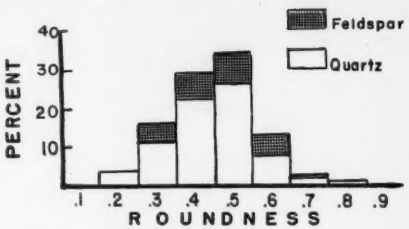

FIG. 4.—Histogram of roundness of all grains (895) from nine samples of Potsdam Sandstone.

According to Pettijohn (1957, p. 555), "the roundness of sand is probably correlated with its mineralogical maturity. The high-purity sands are generally the best rounded; the arkoses and other immature sands are generally the most angular. No quantitative data have as yet been published, so the degree to which the roundness and the quartz content are correlated is unknown." The data in table 1 were used in an attempt to correlate quartz content and roundness, but no relationship was apparent, probably because an insufficient

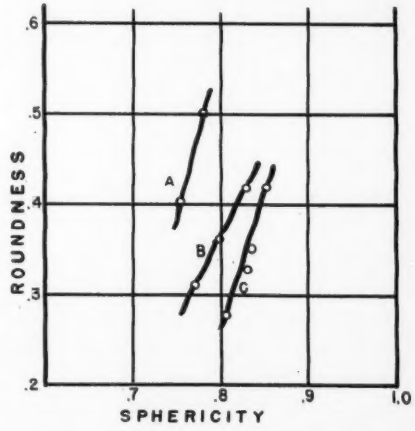

FIG. 5.—Relation of sphericity and roundness. A: Potsdam Sandstone (arkosic and subarkosic), projection sphericity, average of nine samples; B: Lake Erie beach sand, three grade sizes, average of seven samples, projection sphericity, Pettijohn and Lundahl, 1943; C: St. Peter sandstone, four grade sizes, projection sphericity, Wadell, 1935.

number of samples was studied. Cumulative curves showing the roundness of each sample are shown in figure 6.

The mean sphericity of nine samples as shown on table 1 ranges from 0.73 to 0.79. One sample, MOW 8, could not be used, as an authigenic enlargement of both the quartz and feldspar grains made accurate delineation of the grain borders impossible.

Cursory examination of six thin sections of sandstone from the Theresa Dolomite permits the observation that the grains in these samples are very spherical and very well rounded—at least within the Mooers Quadrangle.

DISCUSSION

The derivation of parameters from thin sections of sedimentary rocks in this study seems to provide data sufficiently accurate for use in paleoecologic and sedimentation studies. The compositional data compared in table 1 indicate clearly that the Potsdam cannot be considered an orthoquartzite in the Mooers area; the chemical analyses verify the grain-count analyses, and 25 addi-

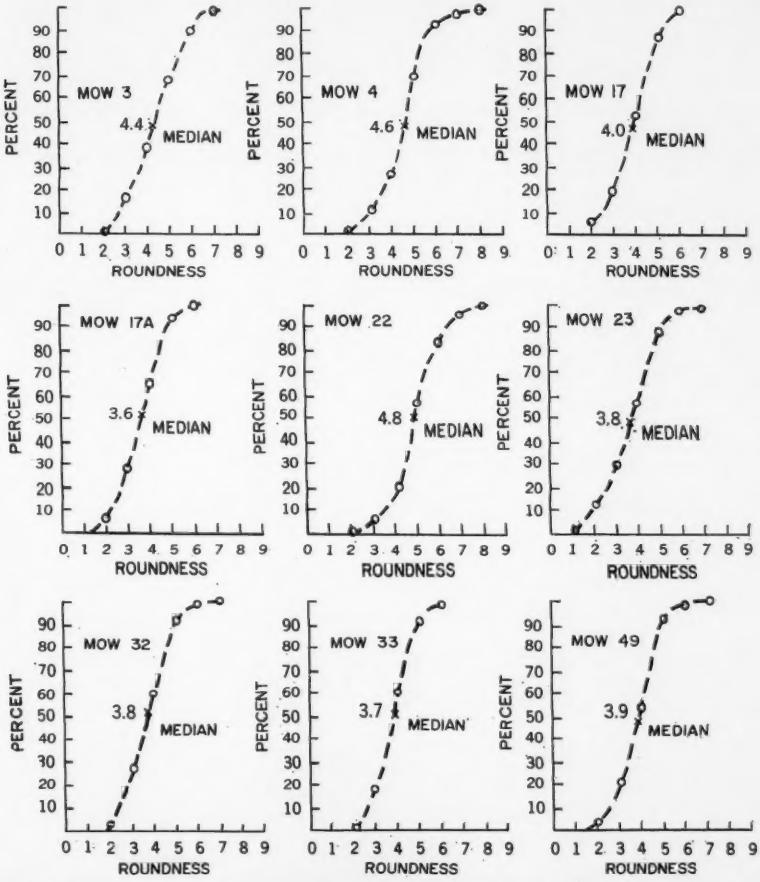

FIG. 6.—Cumulative frequency curves of roundness of nine samples of Potsdam Sandstone.

tional unlisted thin-section examinations provide supporting evidence that is in rather good agreement.

It is apparent that the Potsdam in the Mooers area was deposited quickly and was not reworked because the feldspar has not been removed. It also is apparent that the Cambrian sources of sediment were not entirely areas undergoing deep chemical weathering which would have removed the feldspar prior to and during deposition. Furthermore, the red shale and siltstone within the Potsdam in the Mooers Quadrangle (fig. 2) is much more "logical" in a subarkosic terrane than in an orthoquartzite terrane.

Depositional Environment

Variation in composition of the Cambrian and Ordovician rocks provides a means to evaluate the depositional environment of the sediment. Figure 2 shows the lithofacies of the Potsdam Sandstone. In the Mooers Quadrangle the sedimentation during the Cambrian resulted neither in a typical orthoquartzite-carbonate association nor in a typical arkosic-red bed association.

What therefore is the significance of this mixture of facies? The most obvious explanation is that in the Mooers area the arkose, subarkose, and red siltstone reflect local conditions of deposition such as high relief in the adjoining land mass with rather quick deposition and burial and no reworking of the deposits. The cross-bedding and interbeds of conglomerate attest to the vigor and turbulence of the transporting agent.

What happened farther offshore—to the north and to the east? To the north the effective relief was negligible. As the basin began to fill up, reworking of the sediments was common and the feldspar that had persisted was gradually eliminated chemically as well as mechanically; this part of the Potsdam resembles the orthoquartzite-carbonate facies. As the St. Lawrence embayment was shallower toward the west and as relief on the Adirondack Highland was presumably less to the west, the orthoquartzite-carbonate facies became the dominant phase.

Provenance

In the Mooers area the mineralogy, size, roundness, and sphericity of the Potsdam Sandstone grains clearly indicate that the Adirondack uplands were the initial source areas supplying detrital sand. On a regional basis, however, Adirondack uplands apparrently supplied less sand to the basin than did other areas. The arkosic Adirondack sands ultimately interfingered with and were overlain by the better rounded, feldspar-free, and more spherical sand, presumably from the Canadian Shield.

Transportation

Both the areas of the ancestral Adirondack Mountains south of the Mooers area and of the Canadian Shield north of it contributed sediment to form the Potsdam. However, the Mooers area has been dominated by the sediments from the Adirondacks. The arkosic composition of the Potsdam in the Mooers Quadrangle indicates rapid transportation—as do the beds of conglomerate in the lower layers. The cross-bedding shows current action was easterly, toward the deeper part of the area of deposition. The moderate sphericity and rounding in the Mooers area is consistent with the short transportation and proximity to the Adirondack Mountains.

Figures 7 and 8, which show the relation of roundness and sphericity as a function of distance from the nearest Precambrian rock in the Adirondack Mountains, would have little significance if the Canadian

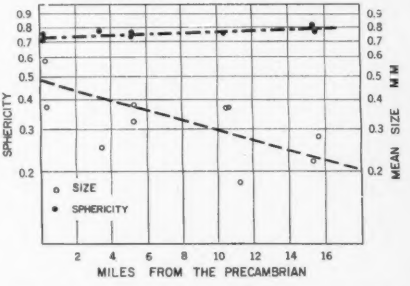

FIG. 7.—Mean size (after Krumbein, 1935) of 10 samples of Potsdam Sandstone and mean sphericity of nine samples of Potsdam Sandstone and mean sphericity of nine samples of Potsdam Sandstone as a function of the distance from the nearest Precambrian rock, presumably the source rock.

Shield source had been a heavy contributor of sediment in the Mooers Quadrangle. Because the Adirondack area was almost the sole source in this quadrangle, the data possess greater significance.

The coefficients of sorting (S_0) are shown in table 1 for each of the 10 samples. In figure 9 the coefficient of sorting is plotted against the present dip of the beds (taken by Brunton compass) from which the sample was obtained. There is a rough correlation between degree of sorting and steepness of dip. It is also worthy to note that the median size also increases as the dip increases, though this trend is not shown graphically.

Tectonic Significance of Arkosic Sedimentation

If the abundance of feldspar in the Potsdam in the Mooers area reflects the stability of the Adirondack positive area and the nearness of the local source rocks, arkose and subarkose should be abundant all along the periphery of the Precambrian rocks and would theoretically be absent in the upper beds. If, however, the feldspar content reflects tectonic instability in the Appalachian Geosyncline to the east, arkose and subarkose would occur at various places in the geologic section. Feldspar is certainly much more abundant in the Potsdam Sandstone of the Champlain Valley (fig. 1) than elsewhere and it occurs both high and low in the stratigraphic section (fig. 2). West of the Mooers Quadrangle it is generally confined to the basal part of the Potsdam.

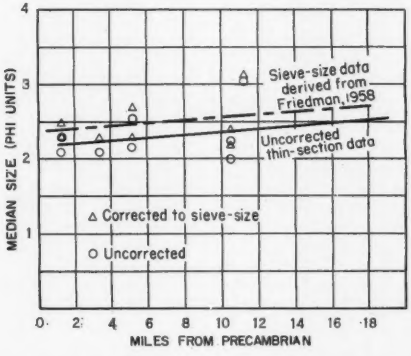

FIG. 8.—Median size (in phi units) of 10 samples of Potsdam Sandstone decreases as the distance from the Precambrian rocks increases.

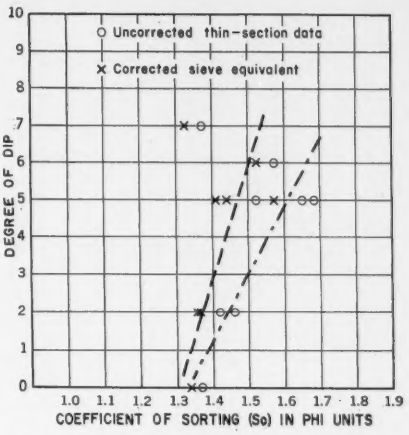

FIG. 9.—Relation of dip of strata to coefficient of sorting. The graph shows rough correlation indicating that the dip is essentially a primary feature.

The red shale and siltstone unit (fig. 2) at the base of the Potsdam in the Mooers area is unique for the Potsdam. It is feldspathic, ferruginous, rather silty, micaceous, and slightly calcareous. This type of lithology commonly is associated with arkose. Neither arkose nor red shale and siltstone are typical of stable shelves, and their occurrence here stresses the changing depositional environment of the Potsdam Sandstone.

In contrast to the arkosic terrane of the Lake Champlain region much of the rock classed as Potsdam near the type locality to the west is typical stable-shelf orthoquartzite.

The increase in arkose in the Lake Champlain area leads to the inference that tectonism—or at least relief—was strongest in this area. The most apparent surface evidence of regional tectonism is the normal faulting in the Lake Champlain region, some of which extends into the Mooers Quadrangle.

Faulting in the Lake Champlain region affects rocks as young as Trenton in age, but the increase in arkose toward the center of extensive tectonic activity gives rise to the interesting speculation that some of the nor-

mal faults in the Lake Champlain region may be related to tectonic activity either preceding deposition of the Potsdam or contemporaneous with this deposition.

Evidence of tectonic activity in the Precambrian massif in nearby areas is not lacking. Potsdam sandstone occurs just south of the Mooers Quadrangle at an altitude of 2800 ft atop Johnson Mountain, which is believed to be a block-faulted feature (Postel, A. W., oral communication); the diabase dikes and the joint systems of the Precambrian rocks generally follow the joint and fault directions in the Paleozoic rocks; granite breccias and diabase breccias are not uncommon (Postel, A.W., oral communication).

CONCLUSIONS

Much quantitative information of value to the sedimentary petrologist can be obtained by measurement of established parameters in thin sections of hard, well-indurated sandstones. The data obtained can furnish information for paleotectonic-studies, lithofacies maps, and stratigraphic studies. Care should be exercised, however, in comparing the results of separate studies that have used diverse types of statistical analysis such as projection sphericity and thin-section sphericity.

The Potsdam Sandstone ought not to be characterized as a typical shelf-type orthoquartzite; in the Mooers area it is chiefly a subarkose and arkose.

The sandstone beds in the Theresa Dolomite can be distinguished from the Potsdam Sandstone in the Mooers area. In the Potsdam Sandstone detrital zircon is a common and widespread mineral, although it never constitutes as much as 1 percent of the sample; in thin sections of the Theresa, zircon does not occur. Feldspar in the Potsdam is very abundant, whereas in the Theresa it is very rare and much smaller than the quartz. Roundness and sphericity values are moderate in the Potsdam but very high in the Theresa. The Theresa also seems to be well sorted.

It must be pointed out that these differences do not hold true farther west where the Potsdam is well rounded and orthoquartzitic for one-half to three-quarters of its thickness.

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FIGS. 1–15, MARCH, 1961

SIGNIFICANCE OF COMPOSITIONAL AND TEXTURAL PROPERTIES OF SOUTH CANADIAN RIVER CHANNEL SANDS, NEW MEXICO, TEXAS AND OKLAHOMA[1]

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ABSTRACT

Size distribution parameters and mineralogical composition of South Canadian River channel sands remain essentially constant over approximately 650 miles of river distance. Mean roundness, mean sphericity, and mean shape factor values of some minerals in the channel sediment increase downstream, while these values decrease for others. However, most minerals show no significant variation in these properties either downstream or between size grades. Quartz-feldspar ratio increases significantly downstream in only two size grades.

A brief review of size distribution and particle morphology parameters is given.

INTRODUCTION

General Statement

This paper is based on a study of the mineralogical composition and the textural properties of channel sediment of the South Canadian River, New Mexico, Texas, and Oklahoma. Surficial samples of sediments from the low water channel of the river were collected over more or less regularly spaced intervals from near the head-waters in eastern New Mexico to near the mouth in eastern Oklahoma, a distance of approximately 650 miles. These samples were analyzed in order to determine their size distributions and mineralogical content. The roundness, sphericity, and shape factor of the common minerals present were ascertained in the various samples and in the various sizes of individual samples. These properties were treated statistically in order to determine the relationships between these properties and apparent distance of transportation and size, as well as the interrelationships among the properties themselves. Analysis of mineralogical composition, roundness, and shape was limited to the sand size grades. No sizes larger than sand were found in the reach of the river under study.

Previous Work

Size distribution parameters.—Numerous parameters for describing size distributions of sedimentary particles have been devised. Those most commonly used have been defined by Trask (1930, 1932), Krumbein (1936), Inman (1952), Folk (1957), and Folk and Ward (1957). The parameters defined by Trask and Krumbein are based on quartile measurements, that is, based on the 25th, 50th, and 75th percentile of the size distribution. Inman's and Folk and Ward's parameters are based on these percentiles as well as on percentiles closer to the extremes of the distribution and, therefore, yield more discriminating results. Trask's parameters are based on the size measurements in millimeters, the other three on measurements in ϕ scale. Regardless of how the parameters are defined, five different ones are generally used. These are:

1.—Median diameter: that size such that 50 percent of the particles are larger and 50 percent smaller. It is generally preferred to the mean diameter as a measure of central tendency as it is less influenced by skewness and, therefore, serves as a better approximation of the modal diameter.

2.—Mean diameter: the average size.

3.—Sorting or dispersion: a measure of the spread of the distribution. It would correspond, more or less, with the standard deviation of standard statistical methods.

4.—Skewness: a measure of symmetry of the distribution curve. In a normal distribution the mean and median coincide and the distribution curve is symmetrical, but if they depart from each other, the distribu-

[1] Manuscript received March 30, 1960.

tion is skewed. If the mean is greater (in ϕ units) than the median, the curve has a positive skewness; if less, a negative skewness. In a normal distribution the skewness value equals zero.

5.—Kurtosis: a measure of the peakedness of the curve. Curves more peaked than a normal distribution are called leptokurtic; those less peaked, platykurtic.

The parameters used in this paper are those which have been defined by Folk. These are, as mentioned previously, based on percentile measurements in ϕ scale. These parameters and their formulae are as follows (in all the formulae p_n indicates the percentile value n and may be read directly from the cumulative curve):

1.—Median diameter:

$$Md = p_{50} \text{ (This is the 50th percentile)}$$

2.—Mean diameter:

$$Mz = \frac{p_{16} + p_{50} + p_{84}}{3}$$

3.—Sorting: Folk's term is Inclusive Graphic Standard Deviation:

$$\sigma_I = \frac{p_{84} - p_{16}}{4} + \frac{p_{95} - p_5}{6.6}$$

Perfect sorting would give a value of zero with all other conditions giving higher results.

4.—Skewness: Folk's term is Inclusive Graphic Skewness.

$$SK_I = \frac{p_{84} + p_{16} - 2p_{50}}{2(p_{84} - p_{16})} + \frac{p_{95} + p_5 - 2p_{50}}{2(p_{95} - p_5)}$$

In normal distributions $SK_I = 0.00$. The limits of this measure are from $+1.00$ to -1.00. The positive skewness indicates a "tailing" in the larger numbers of the distribution and since the measurement is in ϕ units this "tailing" should be toward the smaller diameters. The reverse would be true for a negative skewness.

5.—Kurtosis: Folk's term is Graphic Kurtosis.

$$K_G = \frac{p_{95} - p_5}{2.44(p_{75} - p_{25})}$$

In normal distributions $K_G = 1.00$. Curves that are leptokurtic have values over 1.00 while those that are platykurtic have values less than 1.00. Theoretically the lower limit to this measure is 0.41 with no upper limit but Folk has indicated that most sediments have a K_G range between 0.60 and 5.00.

Shape measurements.—Until 1932 the shapes of particles were defined and described in various fashions and often such terms as shape, roundness, and sphericity were used indiscriminately and interchangeably. In spite of the fact that numerous workers developed methods of quantitatively measuring shape and roundness, the concept of a particle having more than one distinct and separate property of geometric configuration was not demonstrated until Wadell (1932; 1933; 1934; 1935) clearly defined shape (*sphericity*) and *roundness*. Additional configuration properties have been added by Zingg (1935) called *shape factor* and recently by Sneed and Folk (1958) called *form*. A discussion of the earlier methods of describing particle "shape" may be found in Krumbein and Pettijohn (1938, p. 278–291).

Roundness measurements.—As mentioned above, roundness was first clearly defined quantitatively by Wadell (1935). This was expressed as

$$P(Rho) = \frac{\sum \frac{r}{R}}{N}$$

where P equals the roundness, r the radius of a single grain corner, R the radius of the maximum inscribed circle in a longitudinal section, and N the number of corners measured. These measurements were accomplished by projecting an image of the grain and making the necessary measurements on this image. By this formula a perfectly rounded grain would have a value of 1.00, all others would be less, with 0.00 being the theoretical lower limit. This formula captures the idea of roundness and gives extremely accurate results, but workers found it extremely tedious and time consuming to make the necessary measurements of a sufficient number of grains so that a study might be statistically valid. Because of this objection, numerous visual comparison charts have been devised with the models on the charts being made to conform with roundness values as defined by Wadell.

One of the earliest of the comparison charts was made by Russell and Taylor

(1937) where photographs of grains were arranged in five descriptive roundness classes. Russell and Taylor referred their class limits to the Wadell system but the size range of their classes was arbitrary. Krumbein (1941), using Wadell's formula, prepared a chart showing silhouettes of grains for nine roundness values in arithmetic progression from 0.1 to 0.9. Krumbein made no attempt at division into descriptive classes. Pettijohn (1957, p. 58–59), modified Russell and Taylor's descriptive classes, rearranging them into a geometric progression with larger class ranges in the higher roundness values. This change was felt to be necessary by Pettijohn because "it is difficult to distinguish slight differences in roundness if the roundness values are high but similar differences can be readily ascertained at the lower end of the scale." He also showed a comparison chart illustrating in silhouette approximate mid-point values of his classes. Powers (1953) agreed with Pettijohn's statement quoted above and further stated that "even this geometric scale does not provide small enough divisions in the lower roundness values." Therefore, he constructed a six class system, staying with a geometric progression to achieve greater distinction in the lower roundness values. He constructed clay models of grains of the mid-point values of his classes (testing the grains using the Wadell formula) and then photographed the models so the pictures might be used as a comparison chart. The models were constructed so that for the same roundness value, there were grains of both high and low sphericity.

Beal and Shepard (1956, p. 50–52), in a study of environmental effect of roundness, made an analysis of the determination of roundness by the use of Powers' comparison photographs and Krumbein's silhouettes. They found the roundness results of both comparable, though Krumbein's method gave slightly higher values. In this comparison of methods, they found Krumbein's silhouettes difficult to use for direct comparison with actual grains and, therefore, since both gave approximately the same results regarding roundness, they chose Powers' scale for their complete study. However, after studying more than 200 samples, they reported a fallacy in Pettijohn's and Powers' idea regarding an operator's ability to distinguish roundness differences. They stated that an operator could more easily distinguish differences in roundness when the roundness values were high rather than the reverse and, therefore, they recommended a scale giving fine divisions in the high roundness values.

It appears, then, on the basis of Beal and Shepard's work, that the use of Krumbein's silhouettes, which are arranged in an arithmetic progression, might give more accurate results than Pettijohn's or Powers' if an easy method of comparison with actual grains could be utilized. Such a method has been devised and is described later in this paper under "Methods of Study."

Sphericity measurements.—Wadell (1932) defined true sphericity as a ratio of the surface area of sphere to the surface area of a particle of equal volume as expressed in the formula

$$\psi = \frac{s}{S}$$

where ψ is the sphericity, S the surface area of a particle, and s is the surface area of a sphere of equal volume. Because the determination of the surface area of an irregular particle would involve extremely difficult, if not impossible, integration, he devised an operational sphericity for sand grains that would closely approximate the true sphericity. This is

$$\psi = \frac{d_c}{D_c}$$

where d_c is the diameter of a circle of equal area to the area of the projection of the grain when resting on its largest face, and D_c is the diameter of the smallest circle that can circumscribe this projection.

The operational sphericity of Wadell is also cumbersome to use and because of this Krumbein (1941) defined another operational sphericity by using the measurements of intercepts (axes) of the particle. He compared the particle to a triaxial ellipsoid rather than a sphere. His concept is defined by the formula

$$\psi = \left(\frac{bc}{a^2}\right)^{1/3}$$

where a is the longest intercept, b the inter-

mediate, and c the shortest. Since for most particles the intercept measurements can be more or less easily measured, Krumbein's method has gained wide usage.

Aschenbrenner (1956) has refined Krumbein's intercept sphericity to make it more closely approximate Wadell's original true sphericity by substituting a tetrakaidecahedron for the triaxial ellipsoid as the comparison solid. His sphericity is defined as

$$\psi = \frac{12.8(p^2q)^{1/3}}{1+p(1+q)+6[1+p^2(1+q^2)]^{1/2}}$$

where $q=b/a$, $p=c/b$, and a, b, and c are still the long, intermediate, and short intercepts respectively. He presented a chart whereby the sphericity value may be readily ascertained from the values of the ratios p and q.

Sneed and Folk (1958) presented a variation of Krumbein's intercept sphericity called maximum projection sphericity which they feel takes into account the actual hydraulic behavior of particles. Their sphericity is defined as

$$\psi = \left(\frac{S^2}{LI}\right)^{1/3}$$

where L is the long intercept, I the intermediate, and S the short.

Shape factor and form measurements.—It has been recognized that though sphericity measurements give a quantitative approximation of the equidimensionality of a grain, particles of equal sphericity may not resemble each other in over-all appearance; that is, both a disc-shaped and rod-shaped particle may yield exactly the same sphericity values. To describe this additional geometric property of particles, Zingg (1935) has defined *shape factor*, and Sneed and Folk (1958), *form*. Zingg's shape factor is determined by the formula $F=p/q$, where p and q are the same ratios as in the discussion above on sphericity. Zingg further provided four descriptive shape classes based on the values p and q. In his system a single F value may transgress several of his shape classes. Sneed and Folk defined form in ten classes based on certain areas of a triangle on which a coordinate system had been ruled using the ratios S/L and $L\text{-}I/L\text{-}S$ as the coordinates. S, L, and I refer to the same intercepts as in the discussion above on sphericity. They also provided for a "form ratio" which is based on the number of specimens in a sample that fall into each of their descriptive classes.

River sediment investigations.—Numerous studies have concerned themselves with the changes in clastic sediments with distance (see Pettijohn, 1957, p. 525–587; and Russell, 1939, for a discussion and review of the literature on this phase), but only a few have been restricted to river sediment, and of these, the majority have dealt with pebble sized particles (Krumbein, 1940, 1942; Plumley, 1948; Sneed and Folk, 1958; Miller, 1958). Russell (1936, 1937), Russell and Taylor (1937), portions of the work by Plumley (1948), and van Andel (1950, 1951) are among the exceptions that are concerned with changes in sand sized particles over an appreciable distance of river transportation.

Many of the results of these river studies are contradictory with regard to changes in textural properties and composition with distance. Some differ with respect to their interpretations of interrelationships of properties. Only a few are concerned with variation in properties with change in size of a particle (especially Sneed and Folk, 1958).

DESCRIPTION OF PRESENT INVESTIGATION

Description of River

The South Canadian River (or simply, the Canadian River) and its tributaries drain an area of approximately 47,500 square miles of New Mexico, Texas, and Oklahoma. The drainage basin, which makes up approximately 30 percent of the drainage area of the Arkansas River to which the South Canadian is tributary, is approximately 600 miles long in an east-west direction and approximately 85 miles in average width. The basin extends from eastern New Mexico to eastern Oklahoma.

The principal headwater tributaries of the South Canadian River rise in the Cimarron and Sangre de Cristo Mountains in the northeastern part of New Mexico. The main stem rises near Raton, New Mexico, and flows in a general southerly direction to its confluence with the Conchas River, at the site of Conchas Reservoir; thence it flows easterly across the Texas Panhandle and

through central Oklahoma where it finally enters the Arkansas River near the Arkansas state line (fig. 1). Because Conchas Dam prevents the head-water system from contributing to the main stem below, this study has concerned itself only with that portion of the river below the dam. The length of the river from Conchas Dam to the mouth is 740 miles. The fall of the river varies from approximately 5 ft per mile below the dam to approximately 3 ft per mile near the mouth. The average fall over this distance is approximately 4 ft per mile.

Conchas Dam is built in a canyon approximately 150 ft deep which gradually disappears below the dam. For the remaining distance to the Texas state line, the river intermittently flows in small canyons between high mesas, and the valley continues to deepen until it is some 330 ft below the level of the divides. In the western part of the Texas Panhandle the South Canadian River is entrenched in a relatively narrow canyon that reaches a maximum depth of close to 1000 ft a little west of Amarillo. This canyon effect largely disappears in the eastern part of the Panhandle. In Oklahoma the valley is relatively wide, averaging approximately one mile, and the low water channel is meandering and very shallow. The stream often exhibits braiding. There are very few tributaries to the South Canadian of any significant size, the major ones being Ute Creek which enters the main stream at Logan, New Mexico, Little River which enters above Calvin in eastern Oklahoma, and the North Canadian River which flows into the main stream near Eufaula, Oklahoma, just 38 miles above the South Canadian's conjunction with the Arkansas River.

The headwater streams in New Mexico rise in Cretaceous and Jurassic sediments, part of which are capped by Quaternary lava flows. The lower portions of the headwater tributaries and the main stem above Amarillo are in poorly consolidated Triassic sediments. Throughout the Texas Panhandle and extending into extreme western Oklahoma the South Canadian has cut through the Ogallala Formation of Pliocene age which forms the High Plains, and from Amarillo eastward to central Oklahoma the valley is cut in Permian redbeds. In eastern

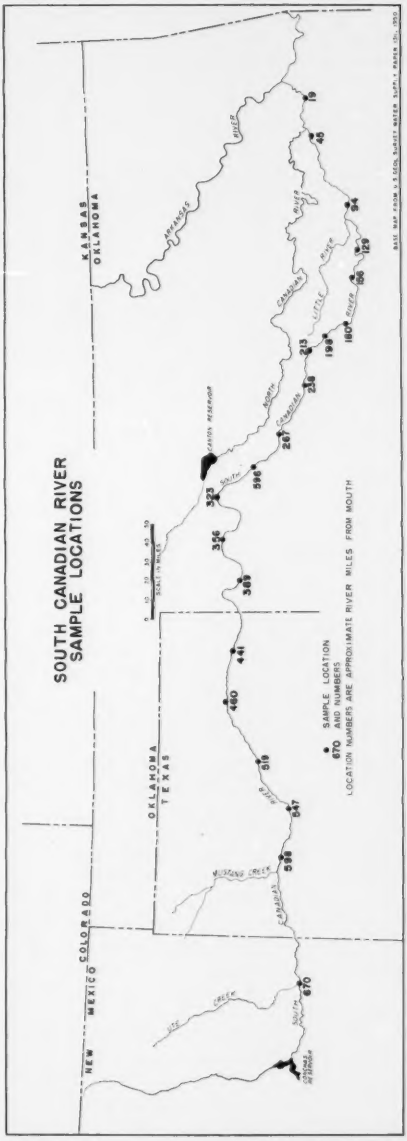

FIG. 1—The South Canadian River, showing sample locations.

Oklahoma the bedrock is Pennsylvanian in age.

The river, in the portion under study, is generally an aggrading stream and is flowing on recent alluvium. It is felt that the material examined in this study has originated, at least during its present erosional cycle, from this fill material.

There is comparatively wide variation in climatic conditions over the length of the river. In the western portion the winters are frequently severe and the summers mild, while in the eastern portion the winters are less severe and the summers are characterized by higher temperatures. The average annual rainfall in the river basin varies from approximately 15 inches in New Mexico to 42 inches in eastern Oklahoma. It is characteristic of the basin, particularly in the western portion, that temperatures and precipitation vary over fairly wide extremes.

Methods of Study

Sampling.—Samples were collected from 20 locations on the South Canadian River channel. The sample numbers indicated on figure 1 and throughout the paper refer to the river-mile distance of the sample location from the mouth of the river. The most upstream sample was collected at Logan, in eastern New Mexico, and the most downstream sample was collected from near the mouth of the South Canadian close to the town of Stigler in eastern Oklahoma.

The samples were collected with a "dredge-like" sampler from the center of the low water channel. This sampler scraped approximately the upper inch of bed load material. Two samples were taken at each location and mixed to form a single sample representing that particular location.

The sampling device was constructed from a steel cylinder which was open at one end. The cylinder was flattened on one side and a beveled lip was riveted at the open end of this side. The flattened side was weighted down by bolting lead weights on the interior of the cylinder. Large eye-screws were fastened on the exterior of each side of the cylinder through which ropes were attached so the sampler could be pulled along the bottom. The holes, through which the bolts and screws went, were soldered so the cylinder was water-tight. By using approximately 10 ft of rope attached to the eye-screws, it was possible to throw the sampler out so the bottom sediment was not stirred by walking in the stream bed at the place the sample was taken. After pulling the sampler a short distance, the device was upturned and withdrawn from the stream with its contained water and sediment. The sample and water were poured into a standard large cloth sample sack and the water allowed to filter through the sack. (An experiment showed that a sample sack makes an excellent filter with essentially no loss of sediment if the water is allowed to drain slowly by itself.) The sampling device proved quite effective and, though there may have been some loss in the "upturning" operation, it is believed that this loss was negligible.

Mechanical analysis.—The samples were dried, split, and weighed for size analysis. At first, an analysis was attempted through the use of the Emery settling tube (Emery, 1938) but, after comparison with sieving methods, it was found that the results from the two methods were inconsistent. Therefore, size analysis by sieving alone was used. The parameters were found as previously mentioned, using the formulae developed by Folk (1957) and Folk and Ward (1957). These parameters are the median, mean, sorting (dispersion), skewness, and kurtosis. Though Folk has qualified the names of these parameters by special terms (for example, his skewness is called Inclusive Graphic Skewness), for the purpose of this paper the general parameter terms alone are used.

Mineral separation.—After sieving, the samples were further split for mineral analysis. It was hoped that the separation could be accomplished by making use of the magnetic properties of the minerals (Krumbein and Pettijohn, 1938, p. 344–348) through the use of the Frantz Isodynamic Separator (Gaudin and Speddin, 1943), but it was found after running numerous samples that much of the quartz had minute amounts of hematite stain which caused these grains to respond magnetically and be collected together with various magnetic fractions. It was felt that the amount of work necessary to separate this quartz from the magnetic minerals did not justify the use of the separator in spite of speed in which the sam-

ples could be run through the machine. For this reason, separations were finally made by conventional heavy mineral separation methods based on the specific gravity of the minerals and the use of a heavy liquid, in this instance tetrabromoethane (Krumbein and Pettijohn, 1938, p. 320–343). These separations were made of the 0.062 mm and 0.125 mm size fraction of each sample. It was found that the amount of heavy minerals present in larger sizes was not sufficient to warrant mineral separation. Because the study of roundness and shape was to be limited to sand size particles, no separations were made of sizes smaller than 0.062 mm.

Mineral, roundness, and shape determinations.—Splits of the light and heavy mineral assemblage of the 0.062 mm and 0.125 mm size fractions and total content of the larger sizes were mounted on glass micro-slides for microscopic examination. Approximately 1000 grains were mounted on each slide. Both Canada Balsam and Lakeside 70 were used as mounting agents.

The minerals present in each slide were identified and counted by making a traverse of the slide using a mechanical stage mounted on a petrographic microscope.

As each mineral grain was identified, its roundness was ascertained and its intercepts measured for the determination of its sphericity and shape factor.

Roundness values were determined by direct comparison with Krumbein's silhouettes (Krumbein, 1941). As mentioned previously, on the basis of Beal and Shepard's work (1956), there appears to be some advantage to Krumbein's arithmetic scale. It was felt that having a progression of nine roundness values for comparison would yield more accurate results than having to compare with six classes as in the Powers' (1953) scale, particularly as there might be significant variations within the classes. Beal and Shepard's main objection to the Krumbein silhouettes was the difficulty in making direct comparisons. It is believed that this problem has been solved. A camera lucida was mounted on the petrographic microscope and a reproduction of Krumbein's chart (one with black background and white grain outline and one with the conventional white background and black silhouettes) was placed on the desk next to the microscope. With the camera lucida prism placed over the ocular of the microscope, an image of the grain being examined could be seen simultaneously with the Krumbein chart. By moving the chart, the image could be superimposed directly upon the proper silhouette and the correct roundness value quickly and accurately determined.

Intercept measurements were also made at the time a grain was identified. Two intercepts parallel to the slide were measured using a micrometer ocular in the microscope. A third intercept, perpendicular to the slide, was measured by focusing the microscope on the bottom and top of the grain with the fine vernier calibrated adjustment knob of the microscope.

From the intercept measurements, the values of p and q as defined by Zingg (1935) were calculated. The sphericity was determined from the chart given by Aschenbrenner (1956) using the values of p and q. The shape factor was calculated from p and q. The formulae for p, q, and shape factor are given above.

As a corollary of the mineral determination, the quartz-feldspar ratio was computed for each sample run.

It became apparent after a preliminary examination of the slides that there were few differences in the character of the sediment regardless of where the samples were collected, and therefore, it was unnecessary to make detailed measurements for all the samples. Of the 20 samples collected on the main stem, 10 were selected for the determinations described above. These samples were more or less evenly spaced and ranged from 50 to 84 miles apart.

It should be emphasized that the determinations of roundness, sphericity, and shape factor were made for each mineral in each size in each of the 10 samples run.

Statistical treatment.—After determining the roundness, sphericity, and shape factor for each grain of each mineral counted, the mean value of each of these properties for an individual mineral in each size at the various locations was computed. Three kinds of data analyses were conducted.

1.—Mean roundness, mean sphericity, mean shape factor, and mean size for each

mineral, and mean quartz-feldspar ratio were plotted against river distance. Because it is logical to examine the linear relationship between mineral characteristic and river distance, a regression line ("best-fitting" line in the least-square sense) was determined for each plot (Dixon and Massey, 1951, p. 153–160). The slope of each of these lines was tested against the statistical hypothesis that the "true" slope equals zero. As a consequence to this test, the slope is considered to be equal to zero or different from zero. A slope that equals zero means no linear trend in these properties over river distance.

2.—For each mineral the existence of a relationship between size and each of the other mineral characteristics (roundness, sphericity, and shape factor) was evaluated; in addition, the relationship between the quartz-feldspar ratio and size was also examined. Each sample was divided into "small" and "large" groups on the basis of size (the 0.062 mm and 0.125 mm size grades in the case of the heavy minerals). For the other characteristics, an over-all median (a median for the combined "small" and "large" groups) was determined. Each of the "small" and "large" samples was placed into a "low" or "high" characteristic group, "low" or "high" determined by a split at (or near) the over-all median of the characteristic. Thus, a double dichotomy which generates four classes was established. If size and any other characteristic are independent (that is, if there is no relationship between them), there should be as many "small" samples with "low" characteristic values as there are "large" samples with such values (Dixon and Massey, 1951, p. 187–190). Under the hypothesis of independence, a set of theoretical frequencies for the four classes may be determined. If the obtained frequencies in the four classes are similar to the theoretical frequencies, there is no basis for rejecting the hypothesis of independence; that is, the premise that there is no relationship between the property and size is accepted. If the obtained frequencies are different from the theoretical frequencies, the hypothesis of independence is rejected and the premise that a relationship does exist between the property and size is accepted. Chi-square (Dixon and Massey, 1951, p. 187–190) was used to evaluate the discrepancies between theoretical and obtained frequencies; therefore, Chi-square was used to evaluate the existence of a relationship between size and the other characteristic. As a result of this test, a relationship between size and another characteristic is considered to exist or is considered not to exist.

3.—For each mineral, the interrelationships among sphericity, roundness, and shape were evaluated. First, the relationship between each property and size was examined. If the property and size were related, the evaluation of the relationship between that property and any other was made separately for each of the size groups. If there was no relationship between size and either of the properties being considered, the "small" and "large" samples were combined, and one test was conducted. Such a procedure succeeds in removing most of the effects of size upon the relationship between the two properties studied. Each of the two characteristics was dichotomized at (or near) its median, and four classes are formed from the double dichotomy. A Chi-square test of independence between the two variables is conducted in the same manner as in (2) above.

Each kind of analysis described above demands a criterion for rejecting an hypothesis of no relationship ("slope equals zero" is equivalent to "no linear relationship"). A level of significance of 0.05 was used in this study as such a criterion. This level of significance may be interpreted in the following ways: even when the statistical hypothesis of no relationship is correct, sample slope and Chi-square values will depart from zero because of sampling fluctuations. Great departures from zero will occur with low probability, but they will occur; hence a cut-off point which defines "too improbable" must be established. In this paper, a slope of Chi-square value which departs from zero by such a large amount that its occurrence under the hypothesis of no relationship is 0.05 or less is regarded as "too improbable" for the hypothesis to be correct. Given such a statistic-value, the hypothesis of no relationship is rejected and the relationship is said to be "significant." "Non-significant" results merely state that

the no-relationship hypothesis is consistent with the data obtained.

RESULTS OF INVESTIGATION

Size Analysis

Table 1 shows the size parameters for each of the samples collected. It should be noted that the mean and the median diameters are essentially identical in each of the samples. The mean of all the samples is 2.57ϕ for the median diameter and 2.58ϕ for the mean diameter, with a range of 1.80ϕ to 3.60ϕ for the median diameter and a range of 1.85ϕ to 3.61ϕ for the mean diameter. The sorting ranges from 0.48ϕ to 0.99ϕ. Mean sorting for all the samples is 0.65ϕ. According to Folk (1957) these sands would be considered "moderately sorted." Skewness values range from +0.08 to −0.04. The mean skewness for all samples is +0.02. Considering that normal distribution gives a skewness of 0.00 and that the limits of skewness are +1.00 and −1.00, the range of skewness values is small. The kurtosis value range is low, varying from 0.86 to 1.13. Mean kurtosis value for all samples is 1.00.

From inspection of table 1, it can be seen that in each of the samples the mean and median diameters closely correspond, the skewness approximates 0.00, and the kurtosis is close to 1.00. Or in other words, in each of the samples the distribution is essentially normal.

TABLE 1.—*Size distribution parameter values*

Sample	Median ϕ	Mean ϕ	Sorting ϕ	Skewness	Kurtosis
670	2.80	2.85	0.57	+0.08	0.86
598	2.50	2.48	0.83	−0.02	1.01
547	1.80	1.85	0.68	+0.07	0.99
519	2.55	2.53	0.64	−0.03	0.99
469	2.32	2.32	0.50	0.00	0.90
441	2.25	2.29	0.69	+0.06	0.92
389	2.25	2.25	0.59	0.00	1.00
356	2.90	2.92	0.99	+0.02	0.99
323	2.50	2.51	0.64	+0.02	0.98
296	2.38	2.38	0.53	0.00	1.08
267	2.59	2.67	0.64	+0.05	0.95
238	2.40	2.38	0.48	−0.04	1.01
213	2.80	2.85	0.59	+0.08	1.13
198	2.61	2.64	0.62	+0.05	1.04
180	2.80	2.83	0.67	+0.04	1.10
152	2.50	2.52	0.61	+0.03	1.01
129	3.00	2.99	0.83	−0.01	0.97
94	2.80	2.80	0.61	0.00	1.03
45	3.60	3.61	0.57	+0.02	1.05
19	2.05	2.07	0.70	+0.03	1.07

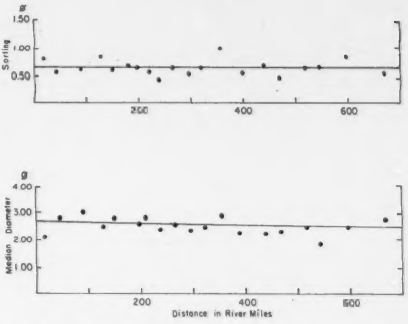

FIG. 2—Sorting and median diameter vs. distance.

The five size parameters were plotted against river distance as shown on figures 2 and 3. With the exception of kurtosis, there is no significant linear trend in the size parameters over approximately 650 miles of river distance. The kurtosis, though the range of values is low, does show a significant increase downstream; that is, the distribution curves tend to become slightly more peaked. This is probably caused by an increase in the grain population of the modal class, but interestingly enough this trend is not accompanied by any significant decrease in the sorting values which would indicate better sorted sands. The formulae for the regression lines of all the size parameters on distance are given in table 6.

Pettijohn (1957, p. 532–533) stated, " . . . in general the size of the clastic ele-

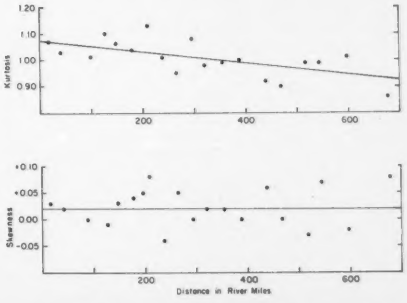

FIG. 3—Kurtosis and skewness vs. distance.

ments carried in a current progressively decreases in the direction of transport . . . although the rate of size decline varies widely in different situations, theoretically the direction of current flow and perhaps distance of transport of a clastic sediment could be estimated by mapping the maximum or mean size of the clastic elements and by drawing isopleths through equal size values and sketching normals thereto." Certainly, if the sands of the South Canadian River constituted some unknown channel deposit this could not be done.

The constancy of the parameters might at first seem odd, but considering that the gradient of the stream is fairly uniform (5 ft per mile to 3 ft per mile) over the distance studied and that each of the samples was obtained from essentially the same position in the channel, it is believed that all samples represent deposits of a similar hydraulic environment, and, therefore, all samples should have very similar size distribution.

Statistical tests were run to examine the interrelationship of the size parameters, and no relationships were found to be significant. This is contrary to the results reported by Folk and Ward (1957) for the Brazos River bar, but they were dealing with bimodal distributions over a relatively large size range with large variance in the parameters, as compared to the unimodal, small parameter variation condition present in the South Canadian. The South Canadian River size parameters behave according to the theoretic premise that the parameter measures are independent.

Mineralogical Composition

Heavy minerals.—The percentage by weight of heavy minerals present for each sample in the two size grades for which the separation was made is given in table 2. These percentages range from 6.69 percent to 1.31 percent in the 0.062 mm size grade and from 1.04 percent to 0.27 percent in the 0.125 mm size grade. As would be expected, the smaller size consistently has higher percentages of heavy minerals. No significant change in the percentage of heavy minerals present in either size occurs in the South Canadian River over the distance studied (fig. 4). This agrees with the results reported by Russell (1937) for the Mississippi River.

TABLE 2.—*Percentage of heavy minerals by weight*

Sample	Size grade (mm)	
	.062	.125
670	1.56	0.42
598	3.51	0.61
547	4.63	0.93
519	1.52	1.00
469	1.31	0.35
441	2.00	0.40
389	1.76	0.60
356	1.62	0.96
323	4.07	0.63
296	3.14	0.66
267	6.69	0.78
238	2.35	0.64
213	1.68	0.37
198	1.53	0.27
180	2.00	0.43
152	5.73	1.04
129	1.76	0.53
94	2.07	0.63
45	2.63	0.68
19	4.31	0.72

The heavy minerals present in the 0.062 mm and 0.125 mm size grades were studied in the 10 samples mentioned previously. Most common of the minerals present are magnetite, zircon, hematite, sphene, spinel-garnet (not differentiated), leucoxene-ilmenite (not differentiated), amphibole-pyroxene (not differentiated), and tourmaline. The several varieties of these minerals constitute more than 95 percent of the heavy minerals present in each slide studied. No other mineral is present in percentages greater than 1 percent. Table 3 shows the percentage by count of these common minerals in the heavy mineral suite (consider-

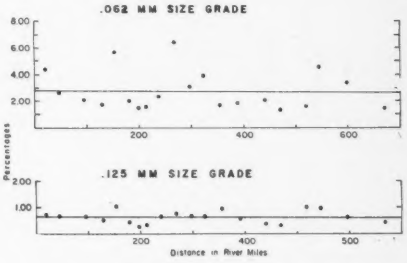

FIG. 4—Percentage of heavy minerals vs. distance.

TABLE 3.—*Percentage of common heavy minerals in heavy mineral suite*
(Total heavy mineral suite—100 percent)

KEY

M—Magnetite	S-G—Spinel-Garnet
Z—Zircon	L-I—Leucoxene-Ilmenite
H—Hematite	A-P—Pyroxene-Amphibole
S—Sphene	T—Tourmaline

Sample	Size Grade (mm)	M	Z	H	S	S-G	L-I	A-P	T
670	0.062	37	17	15	5	5	6	5	5
	0.125	33	10	16	7	8	11	11	4
598	0.062	42	14	13	6	7	5	5	3
	0.125	38	12	12	8	9	7	6	3
519	0.062	40	14	13	8	8	6	6	3
	0.125	37	14	11	9	9	7	7	3
469	0.062	40	15	15	8	8	5	4	3
	0.125	37	13	14	9	10	6	6	3
389	0.062	38	14	16	9	11	6	3	3
	0.125	36	14	15	11	9	6	3	3
323	0.062	47	14	11	10	9	3	5	1
	0.125	37	17	8	10	10	4	8	4
267	0.062	42	17	14	8	8	4	5	2
	0.125	32	12	13	9	9	9	10	5
198	0.062	34	10	15	14	5	6	7	6
	0.125	34	15	12	14	3	8	10	2
129	0.062	38	16	16	11	9	3	2	2
	0.125	31	15	12	9	8	12	5	5
45	0.062	33	15	10	12	8	9	2	7
	0.125	38	17	13	8	11	6	5	2

ing the total suite 100 percent) in the two sizes for the samples studied. It can be seen that each of the minerals is present in about the same relative abundance in each size of each sample. That is, there is no significant change in the percentages of the common minerals downstream, and though magnetite tends to occur with a slightly high percentage in the smaller size for most samples, there is essentially little difference in the relative abundance between the two sizes.

The fact that each of the minerals present remains in about the same relative abundance leads one to assume that in the South Canadian River:

1.—Selective abrasion is not an important factor in the destruction of either physically or chemically less resistant minerals, as illustrated by the persistence of pyroxene-amphibole.

2.—Because the various minerals present have, in many cases, markedly different shapes and roundness (see below), selective sorting on the basis of these factors is also not important.

In analyzing the progressive changes in mineralogical composition the possibility of tributary dilution should be considered. In the South Canadian, this effect is unimportant. Because the relative abundance of the minerals remains essentially constant, the tributaries are either contributing minerals in the same proportions as are present in the main stream, or, if they are contributing minerals of a different order of abundance, this effect is lost within a short dis-

TABLE 4.—*Quartz-feldspar ratio*

(Ratio determined by dividing amount of feldspar by count into amount of quartz by count)

Sample	Size Grade				All sizes
	.062 mm	.125 mm	.250 mm	.50 mm	
670	11.20	8.84	20.00	17.84	10.74
598	11.26	9.12	19.85	18.00	11.28
519	11.43	9.34	19.83	18.46	10.73
469	11.85	9.61	19.80	18.75	12.62
389	12.06	10.00	19.66	19.44	11.93
323	13.46	12.21	19.37	19.62	12.38
267	13.93	13.07	19.00	20.00	10.21
198	9.33	13.11	19.00	20.01	11.21
129	9.24	13.77	18.97	20.50	11.31
45	9.15	14.08	18.96	20.60	10.25

tance when mixing of the bed load occurs. Russell (1937, p. 1333) reported that in the Mississippi River the effects of influx by tributaries are lost within a very short distance, and van Andel (1951) reports that tributary contribution has only local influence on the mineralogical composition of Durance River sands.

Light minerals.—Quartz and feldspar comprise more than 99 percent of the light mineral fractions of the 0.062 mm and 0.125 mm size grades. They also constituted more than 99 percent of the 0.250 mm and 0.50 mm size grades, in spite of the fact that these two grades were not split into weight fractions. Because of the preponderance of quartz and feldspar in the "lights" of the two smaller sizes and in the total assemblage of the two larger, no other minerals were counted. Feldspar, here, is used in the broadest sense, and no attempt was made to identify the individual minerals in this group.

The relative abundance of quartz and feldspar in each size grade, as well as for all sizes combined, was ascertained as a ratio of the number of quartz grains to the number of feldspar grains. These ratios are given in table 4 and are illustrated in figures 5 and 6. The downstream trend of these ratios and the differences in these ratios between sizes were statistically tested. The behavior of the ratios can be summarized as follows:

1.—Considering the total samples, not broken into size grades, there is no significant change in the quartz-feldspar ratio

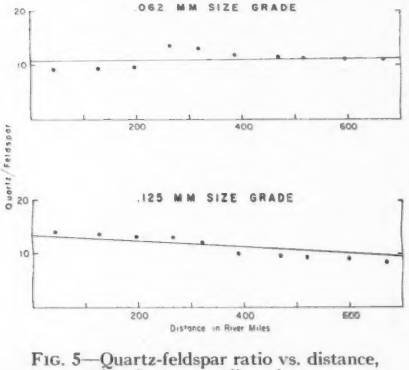

FIG. 5—Quartz-feldspar ratio vs. distance, for the two smallest sizes.

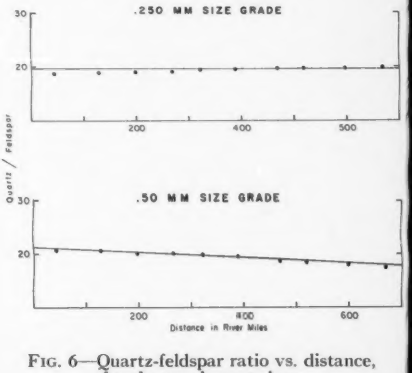

FIG. 6—Quartz-feldspar ratio vs. distance, for the two largest sizes.

with river distance. This is somewhat contrary to the results reported by Russell (1937) who, also dealing with a mixture of all size grades present in Mississippi River sands, reports small but significant increase in the ratio from Cairo, Illinois, to the Gulf of Mexico.

2.—On the basis of the actual values of the ratios, there are two size groups: a small one (0.062 mm and 0.125 mm size grades), within which there is no significant difference in the values between sizes, and a large one (0.250 mm and 0.50 mm size grades), within which there is also no significant difference in the values between sizes. The larger size group has higher quartz-feldspar ratios than the smaller.

3.—Within each of these two major groups, the larger size grade shows a small but significant increase in the ratio downstream while the smaller size grade does not. It should be noted, however, that in the 0.062 mm size grade, though the regression line for the entire distance tested as a zero slope and, therefore, indicates no trend, if shorter distances are considered, there is a slight downstream increase and then a decrease. This reversal is not present in the other size grades.

It appears, then, that the amounts and the downstream variations in the amounts of feldspar in comparison with quartz are dependent upon size. The absence of a trend in the smaller size grades of the two groups may be caused by an "artificial influx" of feldspar in the small size caused by cleavage of particles of the larger size. Also, as indicated by the low range of values even in those sizes where there is a significant trend, the removal of feldspar by abrasion or weathering is a slow, if operative, process. Russell (1937) drew similar conclusions about the removal of feldspar from the Mississippi River.

Roundness

The roundness values of all the grains counted were determined by comparison with the silhouette chart prepared by Krumbein (1941), and the mean roundness for each mineral in each size (0.062 mm and 0.125 mm size grades for the heavy minerals and 0.062 mm, 0.125 mm, 0.250 mm, and 0.50 mm size grades for the light minerals) of the 10 samples analyzed was computed. These mean roundness values by mineral and size are given in table 5. It can be seen from this chart that, though different minerals may have similar roundness values, many have greatly dissimilar values. Furthermore, variations in these values tend to be different for a particular mineral. Sneed and Folk (1958) reported similar conditions for chert, limestone, and quartz pebbles from the Colorado River. In the South Canadian River it is also noted that for some minerals the roundness values for one size differ from those for another size. This difference was tested and the following are found to be significantly different:

Zircon: higher roundness in the larger (0.125 mm) size grade.

Sphene: higher roundness in the larger (0.125 mm) size grade.

Pyroxene-amphibole: higher roundness in the larger (0.125 mm) size grade.

Feldspar: higher roundness in two larger sizes (0.250 mm and 0.50 mm) as compared to the two smaller sizes (0.062 mm and 0.125 mm), but the two smaller sizes when compared to each other and the two larger when compared to each other show no significant difference.

It can be said, then, that if there is a significant difference in roundness of a mineral according to size, the larger size is consistently rounder. This agrees with most previous work (Pettijohn, 1957, p. 63–64).

Roundness values were also plotted against river distance to see if there is any significant change in roundness downstream. The following show a trend:

Sphene: roundness increases downstream in the larger (0.125 mm) size grade.

Leucoxene-ilmenite: roundness increases downstream in both the 0.062 mm and 0.125 mm size grades.

Hematite: roundness increases downstream in both the 0.062 mm and 0.125 mm size grades.

Pyroxene-amphibole: roundness increases downstream in only the larger (0.125 mm) size grade.

Tourmaline: roundness increases downstream in only the larger (0.125 mm) size grade.

TABLE 5.—*Mean roundness, mean sphericity, and mean shape factor values*

Sample	Size Grade (mm)	Mean Roundness	Mean Sphericity	Mean Shape Factor
		Magnetite		
670	0.062	0.58	0.88	0.85
598		0.62	0.85	0.94
519		0.59	0.83	0.87
469		0.58	0.81	0.83
389		0.54	0.77	0.69
323		0.56	0.73	0.66
267		0.62	0.81	0.73
198		0.57	0.84	1.05
129		0.57	0.83	0.86
45		0.58	0.85	0.93
670	0.125	0.62	0.88	0.87
598		0.62	0.88	0.89
519		0.62	0.88	0.88
469		0.62	0.87	0.86
389		0.59	0.88	0.84
323		0.65	0.83	0.78
267		0.64	0.86	0.84
198		0.62	0.85	0.87
129		0.61	0.83	0.92
45		0.61	0.78	0.73
		Zircon		
670	0.062	0.50	0.92	1.05
598		0.61	0.88	1.22
519		0.57	0.87	1.18
469		0.59	0.86	1.15
389		0.56	0.85	1.00
323		0.54	0.82	1.02
267		0.52	0.89	1.16
198		0.60	0.87	1.06
129		0.55	0.88	1.24
45		0.61	0.91	1.29
670	0.125	0.62	0.88	0.95
598		0.64	0.90	0.98
519		0.64	0.90	1.00
469		0.64	0.91	1.01
389		0.63	0.89	1.09
323		0.63	0.88	0.95
267		0.64	0.91	0.90
198		0.60	0.86	0.95
129		0.66	0.92	0.94
45		0.65	0.87	0.89
		Hematite		
670	0.062	0.54	0.91	1.07
598		0.56	0.85	0.94
519		0.55	0.85	0.96
469		0.54	0.84	0.96
389		0.52	0.83	0.98
323		0.55	0.86	0.96
267		0.57	0.82	0.96
198		0.58	0.81	0.94
129		0.59	0.84	0.93
45		0.63	0.91	1.10
670	0.125	0.55	0.88	0.89
598		0.54	0.86	0.84
519		0.55	0.86	0.86
469		0.56	0.87	0.86
389		0.56	0.88	0.90
323		0.58	0.83	0.96
267		0.60	0.87	0.83
198		0.65	0.85	0.93
129		0.65	0.82	0.89
45		0.66	0.80	0.82

TABLE 5.—*Continued*

Sample	Size Grade (mm)	Mean Roundness	Mean Sphericity	Mean Shape Factor
		Sphene		
670	0.062	0.52	0.88	1.04
598		0.53	0.87	1.05
519		0.54	0.87	1.01
469		0.56	0.87	0.96
389		0.58	0.86	0.91
323		0.58	0.82	0.93
267		0.54	0.88	0.91
198		0.60	0.88	0.89
129		0.51	0.89	1.02
45		0.56	0.89	1.15
670	0.125	0.58	0.88	0.95
598		0.60	0.89	0.95
519		0.60	0.88	0.93
469		0.61	0.88	0.90
389		0.61	0.90	0.85
323		0.66	0.89	1.02
267		0.66	0.88	0.94
198		0.61	0.85	0.90
129		0.67	0.90	0.98
45		0.62	0.85	0.95
		Spinel-Garnet		
670	0.062	0.35	0.82	0.91
598		0.42	0.86	1.21
519		0.41	0.86	0.98
469		0.41	0.87	0.97
389		0.41	0.82	0.97
323		0.45	0.78	0.87
267		0.50	0.90	1.00
198		0.47	0.88	1.16
129		0.40	0.83	0.88
45		0.39	0.88	1.14
670	0.125	0.40	0.82	0.91
598		0.42	0.84	1.00
519		0.43	0.85	0.98
469		0.43	0.86	0.96
389		0.43	0.86	0.95
323		0.46	0.86	0.80
267		0.47	0.84	0.87
198		0.47	0.84	0.92
129		0.45	0.88	1.02
45		0.44	0.84	0.80
		Ilmenite-Leucoxene		
670	0.062	0.57	0.87	0.93
598		0.60	0.86	0.96
519		0.55	0.87	0.92
469		0.55	0.87	0.93
389		0.55	0.88	0.92
323		0.56	0.85	0.92
267		0.60	0.82	0.92
198		0.63	0.86	0.90
129		0.66	0.87	0.93
45		0.69	0.89	1.10
670	0.125	0.47	0.86	0.88
598		0.46	0.85	1.05
519		0.46	0.85	0.93
469		0.46	0.84	0.80
389		0.48	0.82	0.75
323		0.50	0.89	1.30
267		0.52	0.90	0.89
198		0.57	0.80	0.78
129		0.62	0.87	0.96
45		0.72	0.80	0.55

TABLE 5.—*Continued*

Sample	Size Grade (mm)	Mean Roundness	Mean Sphericity	Mean Shape Factor
		Pyroxene-Amphibole		
670	0.62	0.43	0.71	0.64
598		0.45	0.66	0.64
519		0.43	0.67	0.63
469		0.43	0.67	0.64
389		0.42	0.69	0.62
323		0.40	0.64	0.60
267		0.47	0.70	0.64
198		0.40	0.71	0.65
129		0.43	0.70	0.64
45		0.45	0.73	0.65
670	0.125	0.46	0.75	0.85
598		0.47	0.74	0.86
519		0.46	0.75	0.86
469		0.46	0.75	0.85
389		0.50	0.76	0.88
323		0.50	0.76	0.82
267		0.50	0.78	0.75
198		0.49	0.73	0.69
129		0.53	0.72	0.64
45		0.53	0.74	0.64
		Tourmaline		
670	0.062	0.68	0.88	1.10
598		0.68	0.84	0.89
519		0.70	0.85	0.88
469		0.70	0.86	0.88
389		0.70	0.84	0.87
323		0.72	0.84	0.87
267		0.72	0.88	0.81
198		0.70	0.84	0.79
129		0.68	0.86	1.21
45		0.68	0.87	1.15
670	0.125	0.62	0.91	1.01
598		0.63	0.90	1.05
519		0.63	0.92	1.11
469		0.63	0.92	1.10
389		0.63	0.92	1.14
323		0.67	0.89	1.05
267		0.70	0.93	1.25
198		0.70	0.92	1.03
129		0.68	0.91	0.98
45		0.68	0.92	1.00
		Quartz		
670	0.062	0.44	0.88	1.08
598		0.44	0.89	1.14
519		0.44	0.88	1.03
469		0.44	0.88	0.99
389		0.44	0.85	0.98
323		0.44	0.85	0.90
267		0.44	0.89	0.90
198		0.44	0.89	1.00
129		0.45	0.89	1.06
45		0.46	0.89	1.14
670	0.125	0.45	0.83	0.80
598		0.45	0.82	0.78
519		0.45	0.83	0.77
469		0.45	0.83	0.76
389		0.45	0.82	0.75
323		0.45	0.84	0.72
267		0.46	0.82	0.70
198		0.46	0.82	0.78
129		0.46	0.85	0.80

TABLE 5.—*Continued*

Sample	Size Grade (mm)	Mean Roundness	Mean Sphericity	Mean Shape Factor
45		0.46	0.86	0.83
670	0.250	0.44	0.77	0.51
598		0.44	0.77	0.50
519		0.44	0.77	0.54
469		0.45	0.77	0.55
389		0.45	0.80	0.58
323		0.45	0.78	0.59
267		0.47	0.81	0.60
198		0.47	0.77	0.60
129		0.45	0.79	0.65
45		0.45	0.80	0.65
670	0.50	0.46	0.78	0.58
598		0.46	0.79	0.58
519		0.46	0.78	0.58
469		0.47	0.78	0.58
389		0.45	0.78	0.58
323		0.45	0.79	0.60
267		0.42	0.78	0.61
198		0.42	0.80	0.64
129		0.42	0.81	0.65
45		0.42	0.81	0.65
		Feldspar		
670	0.062	0.40	0.89	1.00
598		0.40	0.88	1.04
519		0.40	0.88	1.05
469		0.40	0.87	1.09
389		0.40	0.86	1.11
323		0.42	0.86	1.23
267		0.42	0.89	1.27
198		0.42	0.89	1.08
129		0.45	0.88	1.04
45		0.45	0.88	1.02
670	0.125	0.43	0.80	0.84
598		0.43	0.82	0.85
519		0.43	0.84	0.85
469		0.43	0.84	0.87
389		0.43	0.84	0.87
323		0.45	0.84	0.86
267		0.45	0.85	0.86
198		0.45	0.84	0.84
129		0.45	0.86	0.91
45		0.45	0.90	0.94
670	0.250	0.58	0.78	0.52
598		0.58	0.76	0.52
519		0.54	0.78	0.54
469		0.53	0.81	0.54
389		0.48	0.74	0.62
323		0.48	0.81	0.65
267		0.48	0.79	0.58
198		0.48	0.82	0.63
129		0.46	0.76	0.62
45		0.45	0.78	0.60
670	0.50	0.53	0.75	0.60
598		0.53	0.74	0.61
519		0.53	0.75	0.59
469		0.53	0.76	0.57
389		0.51	0.78	0.63
323		0.45	0.80	0.61
267		0.43	0.78	0.59
198		0.43	0.81	0.63
129		0.40	0.82	0.64
45		0.40	0.82	0.64

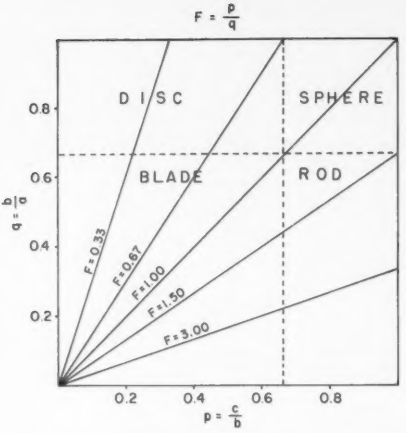

FIG. 7—Shape factor and Zingg shape classes. After Aschenbrenner, 1956.

Quartz: roundness decreases downstream in only the largest (0.50 mm) size grade.

Feldspar: roundness increases downstream in the 0.062 mm size grade but decreases in the largest (0.250 mm and 0.50 mm) size grades.

Plots of roundness values against distance for those minerals which exhibit a significant change in this property are illustrated in figures 8, 9, 10, and 11, and the formulae of all the regression lines are given in table 6.

With the exception of tourmaline, all the

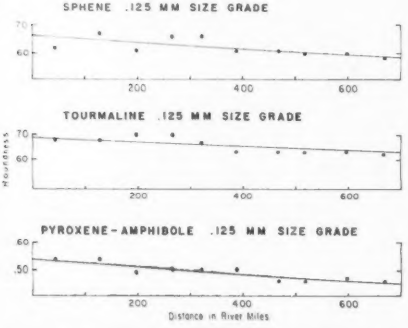

FIG. 8—Roundness vs. distance. (Minerals exhibiting a significant linear trend.)

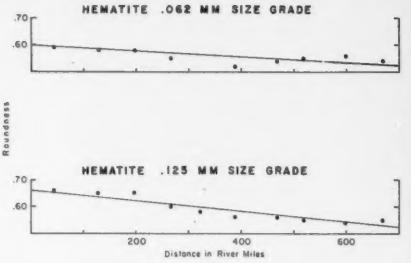

FIG. 9—Roundness vs. distance. (Minerals exhibiting a significant linear trend.)

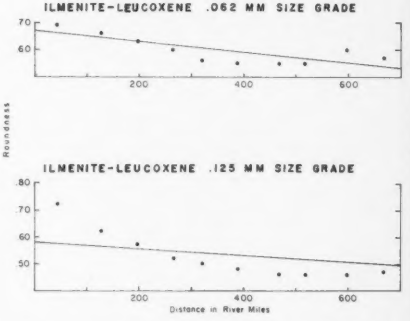

FIG. 10—Roundness vs. distance. (Minerals exhibiting a significant linear trend.)

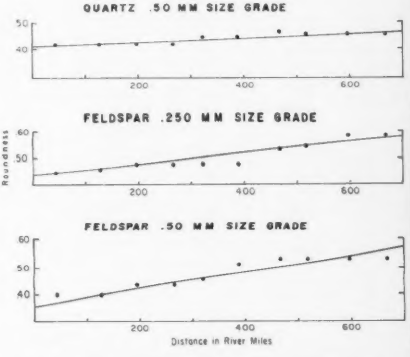

FIG. 11—Roundness vs. distance. (Minerals exhibiting a significant linear trend).

TABLE 6.—*Regression line formulae of sediment characteristics plotted against distance*

These formulae are in the general form, $y=a+bx$, where y is the particular characteristic being plotted, x is the distance, and a and b are constants. The value of b determines the slope of the line. In the following formulae, those that have a significant slope (at a .05 level of confidence) are starred with an asterisk.

Size Distribution Parameters	
Median size ϕ	2.77−0.0007 distance
Mean size ϕ	2.78−0.0007 distance
Sorting ϕ	.63+0.00005 distance
Skewness	.02+0.00001 distance
Kurtosis	1.07−0.0002 distance*

Quartz-Feldspar Ratio	
Size Grade (mm)	
0.062	10.34+0.003 distance
0.125	13.31−0.01 distance*
0.250	19.47+0.0009 distance
0.50	21.12−0.005 distance*

Percentage of Heavy Minerals	
Size Grade (mm)	
0.062	2.82−0.0001 distance
0.125	0.63+0.000007 distance

Mean Roundness

Mineral	*Size Grade (mm)*	
Zircon	0.062	0.56−0.00001 distance
	0.125	0.65−0.00002 distance
Spinel-Garnet	0.062	0.44−0.00007 distance
	0.125	0.47−0.00008 distance
Magnetite	0.062	0.57+0.00003 distance
	0.125	0.62+0.000002 distance
Sphene	0.062	0.59−0.00004 distance
	0.125	0.66−0.0001 distance*
Leucoxene-Ilmenite	0.062	0.67−0.0002 distance*
	0.125	0.57−0.0001 distance*
Hematite	0.062	0.60−0.0001 distance*
	0.125	0.66−0.0002 distance*
Pyroxene-Amphibole	0.062	0.43−0.000007 distance
	0.125	0.53−0.0001 distance*
Tourmaline	0.062	0.66−0.00001 distance
	0.125	0.69−0.0001 distance*
Quartz	0.062	0.45−0.00003 distance
	0.125	0.46−0.00002 distance
	0.250	0.46−0.00004 distance
	0.50	0.41+0.00008 distance*
Feldspar	0.062	0.45−0.00009 distance*
	0.125	0.46−0.00005 distance
	0.250	0.44+0.0002 distance*
	0.50	0.36+0.0003 distance*

Mean Sphericity

Mineral	*Size Grade (mm)*	
Zircon	0.062	0.86+0.00006 distance
	0.125	0.89+0.000007 distance
Spinel-Garnet	0.062	0.87−0.00005 distance
	0.125	0.86−0.00004 distance
Magnetite	0.062	0.81+0.00003 distance
	0.125	0.82+0.0001 distance*
Sphene	0.062	0.88−0.00002 distance
	0.125	0.88+0.00001 distance
Leucoxene-Ilmenite	0.062	0.86−0.00001 distance
	0.125	0.84+0.00003 distance
Hematite	0.062	0.84+0.00002 distance
	0.125	0.82+0.00009 distance*
Pyroxene-Amphibole	0.062	0.72−0.00007 distance
	0.125	0.76+0.00002 distance
Tourmaline	0.062	0.87−0.00003 distance
	0.125	0.92−0.00003 distance
Quartz	0.062	0.88−0.00001 distance
	0.125	0.85−0.00005 distance
	0.250	0.79−0 00005 distance
	0.50	0.81−0.00004 distance*
Feldspar	0.062	0.78−0.000002 distance
	0.125	0.88−0.0001 distance*
	0.250	0.79−0.00002 distance
	0.50	0.82−0.0001 distance*

Mean Shape Factor

Mineral	*Size Grade (mm)*	
Zircon	0.062	0.88 (zero slope)
	0.125	0.94+0.0001 distance
Spinel-Garnet	0.062	1.03−0.00006 distance
	0.125	0.89+0.0001 distance
Magnetite	0.062	0.86−0.00006 distance
	0.125	0.81+0.0001 distance
Sphene	0.062	0.99−0.000005 distance
	0.125	0.89+0.00004 distance
Leucoxene-Ilmenite	0.062	0.98−0.0001 distance
	0.125	0.87+0.00006 distance

TABLE 6.—*Continued*

Hematite	0.062	0.99−0.00002 distance
	0.125	0.87−0.000002 distance
Pyroxene-Amphibole	0.062	0.64−0.00002 distance
	0.125	0.64+0.0004 distance*
Tourmaline	0.062	1.02−0.0002 distance
	0.125	1.05+0.00005 distance
Quartz	0.062	1.01+0.00003 distance
	0.125	0.78−0.00003 distance
	0.250	0.69−0.0003 distance
	0.50	0.64−0.0001 distance*
Feldspar	0.062	1.13−0.0001 distance
	0.125	0.88−0.0004 distance
	0.250	0.63−0.0002 distance*
	0.50	0.64−0.00007 distance*

heavy minerals which increase in roundness downstream have a hardness generally less than 6 while all those which show no significant change are greater than 6. Magnetite, which does not exhibit a downstream trend may be an exception to this, but its hardness spans this critical value, being from 5.5 to 6.5. Also, of the heavy minerals which do become rounder downstream, all but two exhibit this trend only in the larger size, and these two in both size grades. The light minerals, quartz and feldspar, decrease in roundness downstream in the largest sizes.

Possible reasons to explain why some of the minerals show a significant downstream increase in roundness and some a downstream decrease while many did not show any change are:

1.—If abrasion causes an increase in the roundness of particles, the rigor of abrasion in the South Canadian was not sufficient to produce this change except in the softer heavy minerals.

2.—Abrasion may cause a decrease in roundness because of chipping or cleaving of grains. The roundness decrease in the larger quartz and feldspar size grades may be a function of this. Russell and Taylor (1937), reporting a decrease in roundness in Mississippi River sands, attributed it to chipping and fracturing in samples which were essentially all quartz and feldspar.

3.—Some of the minerals might be close to a critical lower limit of roundness whereby additional abrasion would produce no significant changes. Sneed and Folk (1958) report a lower limit of rounding for quartz pebbles of 0.65 on the Colorado River. The highest mean roundness value for any sample of quartz sand in any size on the South Canadian River is 0.47, considerably below the figure for pebbles given by Sneed and Folk.

4.—The size of some minerals might be below some critical point whereby rounding processes are no longer effective. This may by why in most cases only the 0.125 mm size showed a trend while the 0.062 mm size did not.

Any, or all, of the above factors may be involved in the South Canadian, and the rate of change, or lack of change, in these values is dependent on the mineralogy and, for a particular mineral, on the size.

Sphericity

The sphericity was determined by the measurement of intercepts and extrapolation, using these measurements, from a chart given by Aschenbrenner (1956, p. 21). A discussion of the reference solid used by Aschenbrenner has been given in the section, "Previous Investigations." As was done for roundness, the sphericity values were determined for each grain counted and the mean sphericity for a particular mineral in various size grades in each sample was determined. These are given in table 5. Also, the relationship of these mean sphericity values to both size and river distance are examined. The following relationships exist.

1.—Though many of the minerals have the same sphericity values, the size and river distance variations, when they exist, tend to be different for a particular mineral.

2.—Pyroxene-amphibole, tourmaline, quartz, and feldspar show significant differences in sphericity in different size grades. For pyroxene-amphibole the smaller size grade (0.062 mm) is more spherical; for tourmaline the larger size grade (0.125 mm) is more spherical; and for both quartz and feldspar each of the smaller size grades is more spherical than the next larger with the exception of the two largest size grades (0.250 mm and 0.50 mm) which have no significant differences in their sphericity values.

3.—Only magnetite (a downstream sphericity decrease in the 0.125 mm size grade),

hematite (a downstream sphericity decrease in the 0.125 mm size grade), quartz (a downstream sphericity increase in the 0.50 mm size grade), and feldspar (a downstream increase in both the 0.125 mm and 0.50 mm size grades) show significant variation over the course of the river.

The formulae for the regression lines of sphericity versus distance are given in table 6, and the plots of those with significant slopes are shown on figures 12 and 13.

The lower values of sphericity in the larger sizes for all the minerals in which there was a significant difference, except tourmaline, are contrary to values reported by some workers (Pettijohn, 1957, p. 64–65). Although Russell and Taylor (1937, p. 250) stated that "there appears to be a tendency for the larger grains of the Mississippi River to possess . . . higher sphericity values . . . ," they further indicated that "this relationship . . . is not uniformly applicable. . . . "

The fact that most of the minerals do not vary significantly in their sphericity along the course of the river is probably due partly to the same reasons given for the lack of change in many roundness values, namely the lack of abrasional rigor, the possibility of a lower limit of value change, and the possibility of a lower size limit below which the abrasional forces are non-operative. In addition, it has been demonstrated that sphericity is partly a function of the original particle character (Pettijohn, 1957). While there is no apparent system to the changes

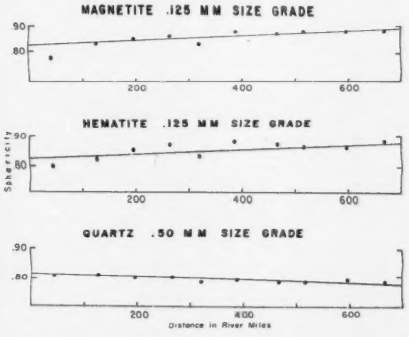

FIG. 12—Sphericity vs. distance. (Minerals exhibiting a significant linear trend.)

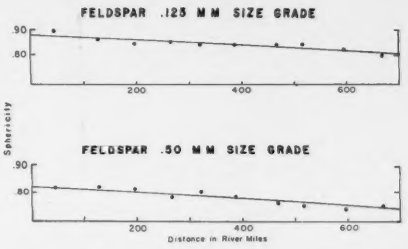

FIG. 13—Sphericity vs. distance. (Minerals exhibiting a significant linear trend.)

that are significant, it is interesting to note that Russell and Taylor (1937) reported a decrease in sphericity downstream in Mississippi River sands that are predominantly quartz in composition, but in the South Canadian River quartz shows a downstream increase in sphericity in the one size grade (0.50 mm) in which a significant change takes place. Sneed and Folk (1958) pointed out that, for Colorado River pebbles, quartz of one size increased in sphericity, one size decreased, while another size remained constant in a downstream direction. They also reported similar variations in the behavior of chert and no systematic changes in limestone pebbles. They stated (p. 149) that sphericity is a "complex function of rock type, pebble size, and distance." The South Canadian River sands bear this out.

Shape Factor

The mean shape factor (F) for each mineral by size and sample was determined from the intercept measurements according to the formulae given by Zingg (1935) whereby

$$F=\frac{p}{q}, \qquad p=\frac{c}{b}, \qquad q=\frac{b}{a},$$

where a is the long intercept; b, the intermediate; and c, the short intercept. This means that

$$F=\frac{\frac{c}{b}}{\frac{b}{a}} \quad \text{or} \quad F=\frac{ac}{b^2}$$

It can be seen that for a given value of the smallest intercept, c, if the values of a and b diverge from each other the F value could

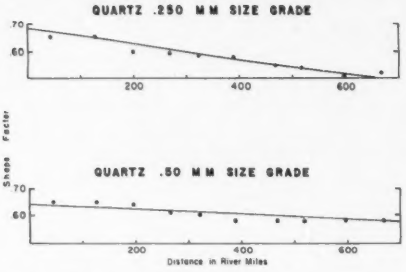

FIG. 14—Shape factor vs. distance. (Minerals exhibiting a significant linear trend.)

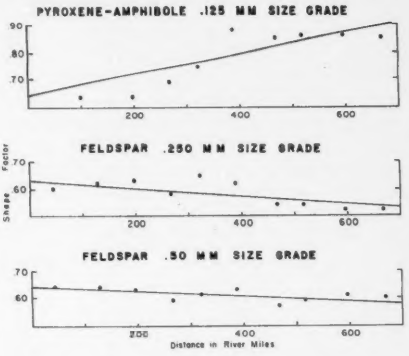

FIG. 15—Shape factor vs. distance. (Minerals exhibiting a significant linear trend.)

get larger and the shape of the grain would tend to become more elongate. Conversely, if the values of a and b approach each other the F values would get smaller and the shape of the grain would tend to become less elongate. These relationships, as well as actual shape classes that Zingg has constructed, are illustrated in figure 7.

The mean F values computed for the minerals in the various sizes in each sample of the South Canadian River are given in table 5. The following minerals show a significant difference in the mean F between sizes:

Hematite: larger F in the smaller (0.062 mm) size grade.

Pyroxene-amphibole: larger F in the larger (0.125 mm) size grade.

Tourmaline: larger F in the larger (0.125 mm) size grade.

Quartz and feldspar: larger F in each successive smaller size grade except the two largest size grades (0.250 mm and 0.50 mm) which have no significant difference.

The mean F value for each mineral in each size was plotted against river distance. The formulae for these regression lines are given in table 6. A few showed a significant change downstream and their plots are illustrated on figures 14 and 15. They are:

Pyroxene-amphibole: decreases in F only the larger (0.125 mm) size grades.

Quartz: increases in F the two largest (0.250 and 0.50 mm) size grades.

Feldspar: increases in F the two largest (0.250 and 0.50 mm) size grades.

It can be seen that, although most of the minerals do not show a significant change with distance, in those that do only the larger sizes are affected.

That most minerals do not exhibit a change in shape factor is probably the result of the same causes as set forth for roundness and sphericity. It is interesting to look, however, at the behavior of quartz and feldspar. Quartz tends to be more elongate in the smaller sizes and also tends to be more elongate downstream in the larger sizes. (Note that the use of the words "more elongate" depends on the interpretation of the Zingg relationships holding the small intercept, c, constant and increasing the F value.) This suggests that quartz may become reduced in size by rolling, although the actual abrasional process might be one of chipping. Feldspar, which is also more elongate in the smaller classes, becomes more elongate downstream in the larger classes as well. This mineral may become reduced in size by cleavage which might produce more elongate small "slivers" from larger particles as well as by the method suggested for quartz. These methods of size reduction seem borne out by the fact that feldspar and quartz decrease in roundness downstream in the larger sizes. It seems significant that all the minerals that show a change downstream also exhibit a significant difference in their shape factor between sizes.

Certainly the shape factor, like roundness

and sphericity, is mainly dependent upon the mineral.

Interrelationship of Roundness, Sphericity and Shape Factor

As has been shown previously that for a given mineral the roundness, sphericity, and shape factor values and the variations in these values over distance are, in some instance, related to the size of a particle. However, the relationship of the mean roundness, mean sphericity, and mean shape factor to each other was found not to be significant for the minerals in South Canadian River sands.

The interrelationships were examined by the method described in the section on "Statistical Treatment." When a property was related to size, comparisons between properties were made for each individual size grade. When the properties were not related to size, the properties were compared regardless of size. These comparisons were made for each mineral.

None of the 10 minerals studied show any significant relationship among these properties.

For Mississippi River sands, Russell and Taylor (1937, p. 248–249) indicated that their data "suggest a relationship" between sphericity and roundness. However, they pointed out that "the data scarcely justify positive conclusions." Sneed (1955, p. 72), working with Colorado River pebbles, found that "there is only slight correlation between particle roundness and particle sphericity" and attributes this slight relationship to a third variable, distance.

It seems that in the study of the interrelationships of these particle properties great care should be taken to eliminate erroneous results caused by the effect of other variables, particularly composition, size, and distance of transport.

SUMMARY AND CONCLUSIONS

The composition and textural properties of the channel sediment of the South Canadian River remain essentially constant over some 650 miles of river distance. When changes in the properties of particles do take place they are dependent on the particular mineral involved and, for a given mineral, on the size of the particle.

Specifically, the following conditions were noted:

1.—The size distribution of all the samples is essentially normally distributed. There are no downstream trends in any of the size parameters except kurtosis, which, though the trend is of a low order, indicates slightly more peaked distribution in a downstream direction. The constancy of the size parameters is attributable to similarity in the hydraulic conditions in the river over the distance studied.

2.—The percentages of heavy minerals in the sediment and the relative abundance of these minerals in the heavy mineral suite show no downstream trend. The 0.062 mm size grade consistently has a greater abundance of heavy minerals than the 0.125 mm size grade but the minerals remain in the same relative abundance between sizes. It is felt that neither selective abrasion nor tributary dilution is an important factor in the South Canadian River.

3.—The quartz-feldspar ratio is higher in the larger size grades (0.250 mm and 0.50 mm) than in the smaller size grades (0.062 mm and 0.125 mm), but within these two groups the values are similar. In the larger size grade of each of these groups (0.125 mm and 0.50 mm) there is a significant increase downstream in the ratio, but in the smaller size grade there is not. It is felt that the reduction of feldspar in the larger size grades to produce the downstream increase in the ratio in these sizes, and at the same time, the absence of a trend in the smaller sizes may be because of an "influx" of feldspar from the large to the small sizes as the particles cleave.

4.—Many minerals show no change in roundness downstream nor significant differences between sizes. Of those that do show a significant difference between sizes, the larger size is consistently rounder. All the heavy minerals that exhibit a trend become rounder downstream, and, although some of these become rounder in more than one size grade, the larger size is always involved. Those heavy minerals that increase in roundness downstream have hardnesses generally less than 6, and it is believed that the abrasional rigor of the South Canadian River was not sufficient to produce an increase in roundness by attrition for minerals

harder than this value. Quartz and feldspar show a decrease in roundness downstream in the larger size grades. This decrease is believed to be a result of chipping and fracturing in the case of quartz and cleaving in the case of feldspar.

5.—Most minerals show no significant downstream trend in sphericity nor significant variation between sizes. Of those that do show variation, some are more spherical in the smaller sizes, some less; some increase in sphericity downstream, some decrease.

6.—The shape factor remains essentially constant both in a downstream direction and between sizes for most minerals. The smaller sizes of quartz and feldspar tend to be more elongate than the larger, and the larger sizes tend to become more elongate downstream. It is believed that quartz and feldspar particles may roll as they are transported which would make smaller, more elongate grains from larger ones, although the actual reduction of size may be the result of chipping. The size reduction of feldspar may also be caused by cleaving which could produce small elongate particles from "parent" particles which are less elongate. The minerals that show a downstream trend in shape factor also have a significant difference in their shape factor between sizes.

7.—The lack of downstream change of roundness, sphericity, and shape factor for most minerals is attributed to a lack of abrasional rigor of the river, the possibility that the values of these properties might be below a critical value whereby no further significant changes may take place, the possibility that size of the particles might be below a critical value whereby the forces to produce the changes are no longer operative, and the effect of the original particle character. Any, or all, of these factors may be involved.

8.—Roundness, sphericity, and shape factor of a particle are dependent on the particular mineral and the size of the particle.

9.—Because the composition of the South Canadian River sands is essentially uniform and the various textural properties remain essentially constant over the course of the river, selective sorting on the basis of roundness and shape is not an important process over the river distance studied.

10.—Many of the commonly used indices for determining direction of sediment transportation, such as a reduction in size of the median diameter, a decrease in the abundance of heavy minerals, a decrease in the abundance of unstable minerals, or an increase in particle roundness and sphericity, do not apply to the channel deposits of the South Canadian River. Therefore, these indices may not always be applicable to other recent or ancient channel deposits.

The above facts agree in part with the results of work reported in other studies of river transported material. Where they do differ, it may be for the following reasons:

1.—Dependency of the properties on size and mineralogy may not have been fully examined. Certainly departures in the results of this study from other studies that have dealt with particles larger than sand size, point out that generalities regarding the characteristics of transported particles cannot necessarily be extended to include all sizes.

2.—The changes that a clastic particle may undergo are so complex, and the interaction of factors in a sedimentary environment are so complicated, that even when comparing sediment from similar environments, such as from river to river, the characteristics of the sediment may differ. Though broad generalizations about the response of sediment to its environment are absolutely necessary, these generalizations may, in fact, mask the true nature of sedimentary particles when the generalizations are applied to a particular environment.

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FIGS. 1–7, MARCH, 1961

CRETACEOUS-TERTIARY CLAY MINERALOGY OF THE UPPER MISSISSIPPI EMBAYMENT[1]

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ABSTRACT

An integrated stratigraphic, paleontologic, and petrologic study shows the presence of three general environments of deposition for the Cretaceous and Tertiary sediments of the Upper Mississippi Embayment: (1) fluviatile, (2) inner neritic, and (3) outer neritic. Prior petrologic studies have shown similar provenance features for all stratigraphic units involved.

X-ray diffraction analyses of 199 clay samples from the three environments and from all the stratigraphic units studied show kaolinite, illite, and montmorillonite as the dominant clay minerals, with small amounts of mixed-lattice and chloritic materials in a few samples. There are three clay mineral assemblages—one dominantly kaolinite, a second dominantly montmorillonite, and a third having nearly equal amounts of kaolinite, illite, and montmorillonite.

The clays of the Eocene (undifferentiated) formations and of the Cretaceous McNairy and Tuscaloosa Formations and the northern part of the Coffee Formation are dominantly kaolinite; those of the Porters Creek, Clayton, and Owl Creek Formations and the Southern part of the Selma Formation are dominantly montmorillonite; and those of the Coon Creek Formation, the northern part of the Selma Formation, and the southern part of the Coffee Formation are kaolinite, illite, and montmorillonite in nearly equal amounts.

Clays deposited in the fluviatile environment are dominantly kaolinite, those in the outer neritic environment are dominantly montmorillonite, and those in the inner neritic environments are composed of nearly equal amounts of kaolinite, illite, and montmorillonite.

Segregation of clay minerals in the depositional environments is believed responsible for these variations in clay mineralogy. Diagenesis and variations in contributions from the source area are believed to be insignificant factors.

INTRODUCTION

There are two prevalent philosophies concerning the distribution of clay minerals in sediments. One considers diagenesis a prime factor in controlling clay mineral associations. The other maintains that difference in contributions from the source area is the prime factor, the differing clay mineral assemblages being the result of segregation of the various clay minerals in the depositional environments.

Obviously no broad generalizations should be made for all sediments, and each case is to be judged on its own merits. Disagreements concerning the origin and distribution of clay minerals in sediments arise from the difficulty of evaluating these factors that control clay mineral composition. Any solution to the controversy must be concerned with both the isolation and evaluation of those factors.

The object of this study was to integrate sedimentary petrology, stratigraphy, and paleontology to form a basis for determining the depositional environments and provenance and then to compare the clay mineral distributions directly with the environments in which they are found. Only on the basis of integrated studies will it be possible to evaluate the relative roles played by diagenesis, contributions from the source area, and segregation of the clay minerals in the depositional environments.

The Cretaceous and Tertiary sediments of the Upper Mississippi Embayment offer an excellent opportunity for such an integrated study of clay minerals because the sediments are relatively young and unconsolidated, their original extent is nearly intact, and they offer a wide range of environments and clay mineral distributions.

STRATIGRAPHIC RELATIONS

The Cretaceous and Tertiary sediments in the Upper Mississippi Embayment reach a maximum thickness of 3200 ft and are Late Cretaceous, Paleocene, and Eocene in age. The stratigraphic column in figure 1 shows the generalized relationships of the lithologic units present.

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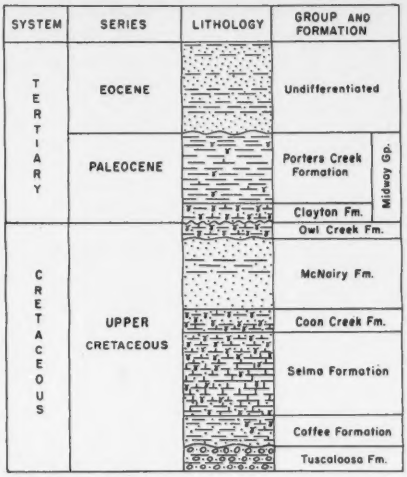

FIG. 1.—Generalized stratigraphic column for Upper Mississippi Embayment.

In the upper Cretaceous (Gulf) Series the basal nonmarine Tuscaloosa Formation is present as a series of limited outliers. The overlying Cretaceous materials were deposited by a deltaic system, heading in the northern part of the embayment and distributing the sediments southward (Pryor, 1960). The deltaic Coffee and McNairy Formations grade southward into the marine Coon Creek and Selma Formations. This gradational sequence was formed by a major transgression and regression (Stearns, 1958, p. 1904, and Pryor, 1960). Unconformably overlying this sequence is the marine Owl Creek Formation.

The Paleocene sediments are represented by the marine Clayton and Porters Creek Formations deposited during the Midway Stage transgression, and these are unconformably overlain by the undifferentiated Eocene sediments.

The nonmarine Eocene sediments represent deltaic and fluviatile deposition in the Upper Mississippi Embayment and grade southward into marine sediments in Mississippi and southeastern Arkansas (Stearns, 1958, p. 1098).

Provenance studies of the upper Cretaceous sediments (Pryor, 1960) and the Eocene sediments (Grim, 1936; Potter and Pryor, in preparation) based on heavy mineral assemblages and directional properties indicate a common source for all units in the embayment. Cross-bedding studies (Pryor, 1960; Potter and Pryor, in preparation) shows sediment transport from the east and northeast. The heavy mineral suites are dominated by metamorphic types such as kyanite, staurolite, and sillimanite, with minor but important quantities of tourmaline and zircon. The source area of the sediments in the Upper Mississippi Embayment is postulated to be chiefly the Blue Ridge and Piedmont Plateau Provinces of the Southern Appalachians (Grim, 1936, p. 116; Pryor, 1960; Potter and Pryor, in preparation).

METHODS

Samples of clay were collected from a wide area (fig. 2) of the embayment from all the upper Cretaceous, Paleocene, and Eocene units. A well spaced sampling design was followed in an attempt to sample each unit over as wide an area as possible.

A field description of each sampled exposure was made to note any features that could be used in interpreting the environment. The samples were split into three fractions—one for clay mineral analysis, one for microfossil separation, and one for insoluble residue and detrital mineral analysis. Samples of sand adjacent to the sampled clay bodies were collected and textural analyses made using the environmental interpretations of Doeglas (1946, 1950) and van Andel and Postma (1954).

Figure 3 summarizes the criteria observed and shows for each unit a general interpretation of environment. On the basis of these criteria, each sample was classified as being from a fluviatile, inner neritic, or outer neritic environment. The presence of fluviatile and deltaic sands, cut-and-fill structures, leaf fossils, and lignite beds in the clay strata or in adjacent beds, and the general absence of the criteria associated with marine environments were chosen as criteria for the nonmarine, fluviatile environment. The presence of mollusca, foraminifera, ostracodes, radiolaria, hystrichospheridae, fish scales and teeth, carbonates, and glauconite was accepted as denoting the marine

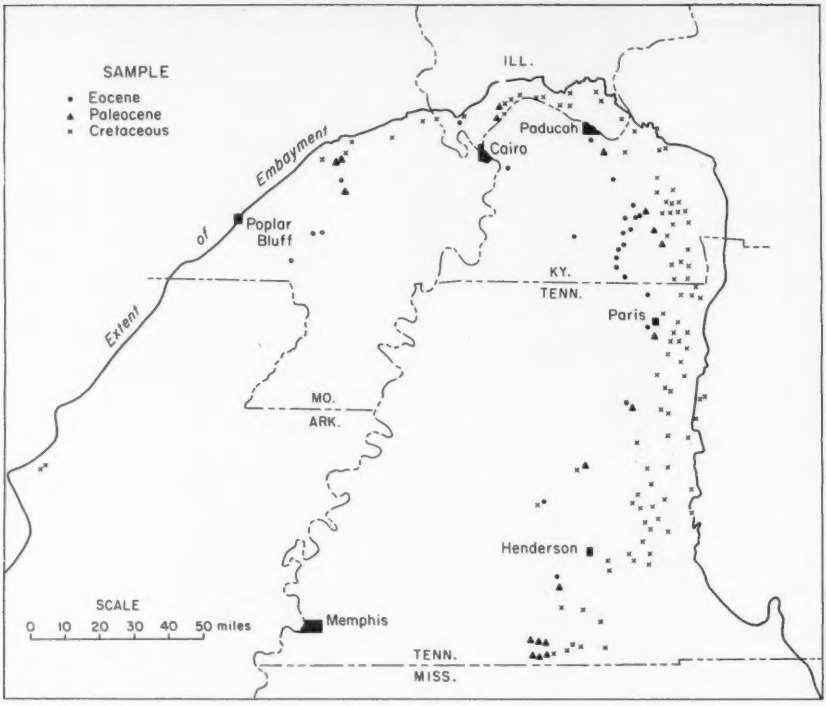

FIG. 2.—Index map showing locations of clay samples.

environment. The abundance of planktonic foraminifera (such as *Globigerina*, *Globigerinoides*, *Globotruncana*, *Globorotalia*, *Gümbelina*) radiolaria, and hystrichospheridae was considered an indication of the outer neritic environment whereas the abundance of benthonic fossils and glauconite indicated an inner neritic environment.

X-ray spectrometer methods were used to analyze 199 clay samples representing the three environments of deposition. Oriented aggregates of the minus 5-micron fraction were made and X-ray patterns were obtained for each sample both before and after ethylene glycol treatment. The abundance of kaolinite, illite, and montmorillonite was estimated on the basis of the relative intensities of the basal (001) sequences and is expressed as parts in ten.

RESULTS

The quantitative results of the clay mineral analyses and the environmental criteria are presented in table 1. The analyses show the presence of three principal clay minerals—kaolinite, illite, and montmorillonite. Very small amounts of mixed-lattice and chloritic material were present in a few samples. Figure 4 shows selected X-ray patterns of the three principal clay mineral associations. These associations are (1) dominantly kaolinite, (2) dominantly montmorillonite, and (3) nearly equal amounts of kaolinite, illite, and montmorillonite.

Clay Mineral Composition of Stratigraphic Units

Figure 5 shows the clay mineral data, plotted by formation, on triangular dia-

TABLE 1.—*Clay mineral analyses and environmental interpretations*

Clay mineralogy (parts in ten)	Environmental criteria	Environmental interpretations

TABLE 1.—*Clay mineral analyses and environmental interpretations*

Clay mineralogy (parts in ten)							Environmental criteria														Environmental interpretations		
Sample	Formation	Kaolinite	Illite	Montmorillonite	Mixed lattice	Chlorite	Lignite beds	Leaf fossils	Fluvial-type sands	Cut-and-fill	Radiolaria	Hystrichosphieridae	Planktonic Foraminifera	Fish scales and teeth	Mollusca	Ostracodes	Benthonic Foraminifera	Shell fragments	Carbonate	Glauconite	Fluviatile	Inner neritic	Outer neritic
ME-1	Undif. Eocene	1.9	2.3	5.8	—	—			X												X		
ME-2	"	1.9	0.8	7.3	—	—		x	X												X		
ME-4	"	4.5	1.6	3.9	Tr.	—			X												X		
ME-5	"	6.9	0.3	2.8	Tr.	—			X	x											X		
ME-6	"	1.3	0.8	7.9	—	—		X	x												X		
IE-1	"	9.5	0.5	—	—	—		x	X	x											X		
KE-1	"	7.6	2.4	—	—	—		x	X												X		
KE-2	"	8.7	0.5	0.8	—	—		x	X	x											X		
KE-3	"	9.3	0.3	0.4	—	—		x	X												X		
KE-4	"	10.0	Tr.	Tr.	—	—	x	x	X												X		
KE-5	"	3.5	3.5	3.0	—	—		x	X												X		
KE-6	"	8.4	1.2	0.4	Tr.	—	x	x	X	x											X		
KE-8	"	9.3	0.7	—	Tr.	—		x	X												X		
KE-9	"	9.0	0.8	0.2	—	—			X	x											X		
KE-10	"	9.0	0.8	0.2	Tr.	—			X												X		
KE-11	"	9.1	0.6	0.3	Tr.	—			X												X		
KE-12	"	8.6	1.1	0.3	Tr.	—			X												X		
KE-13	"	8.3	1.4	0.3	Tr.	—	x	x													X		
KE-14	"	8.4	0.8	0.8	Tr.	—		x													X		
KE-15	"	6.9	2.7	0.4	Tr.	—			X												X		
KE-16	"	8.4	1.2	0.4	Tr.	—		x													X		
KE-17	"	9.2	0.8	Tr.	—	—		x	x												X		
TEhs-1	"	6.5	1.4	2.1	Tr.	—	X	x													X		
TEhs-2	"	5.3	3.5	1.2	—	—	X	x	x												X		
TEhs-3	"	8.8	0.8	0.4	Tr.	—		x	X	x											X		
TEc-1*	"	5.5	4.5	—	Tr.	—															X		
TEw-2*	"	8.7	1.3	—	—	—		x													X		
TEw-3*	"	1.3	3.8	4.9	—	Tr.			x												X		
MPpc-1	Porters Creek	0.5	1.2	8.3	—	—					X	x			x					x			X
MPpc-6	"	0.5	1.4	8.1	—	—					X	x		x									X
IPpc-1	"	0.3	0.5	9.2	—	—					x	x		x									X
IPpc-2	"	0.3	0.9	8.8	—	—					x	x											X
IPpc-3	"	0.7	0.5	8.8	—	—					X	X		x	x								X
IPpc-4	"	0.7	0.7	8.6	—	—					x									x			X
IPpc-5	"	0.8	0.6	8.6	—	—					X			x	x					x			X
IPpc-6	"	0.6	0.5	8.9	Tr.	—					x			x									X
IPpc-7	"	0.7	1.1	8.2	—	—							x	x									X

* Core Sample. X = Abundant. x = Present.

(*Table 1 continued on following pages*)

TABLE 1.—*Continued*

Sample	Formation	Clay mineralogy (parts in ten)					Environmental criteria													Environmental interpretations		
		Kaolinite	Illite	Montmorillonite	Mixed lattice	Chlorite	Lignite beds	Leaf fossils	Fluvial-type sands	Cut-and-fill	Radiolaria	Hystrichosphieridae	Planktonic Foraminifera	Fish scales and teeth	Mollusca	Ostracodes	Benthonic Foraminifera	Shell fragments	Carbonate	Glauconite	Fluviatile	Inner neritic	Outer neritic
IPpc-8	"	0.6	0.4	9.0	—	—						x											X
IPpc-9	"	0.4	0.6	9.0	—	—					X	X								x			X
IPpc-10	"	0.4	0.5	9.1	—	—					X			x	x								X
IPpc-11	"	0.4	0.5	9.1	—	—					X	x			x					x			X
IPpc-12	"	0.6	0.7	8.7	—	—					x	X		x									X
IPpc-13	"	0.7	2.1	7.2	—	—					x												X
IPpc-14	"	0.5	2.0	7.5	—	—					X	X								x			X
IPpc-15	"	0.8	2.1	7.1	—	—					x	X											X
KPpc-1	"	1.1	0.4	8.5	—	—					X	X	x		x					X			X
KPpc-2	"	0.6	1.6	7.8	—	—					X	x								x			X
KPpc-3	"	1.8	2.6	5.6	—	—					X	x		x									X
TPpcc-1	"	1.0	2.0	7.0	—	—					X		x		x		x			x			X
TPpc-10	"	1.3	1.9	6.8	—	Tr.					x	x			x								X
TPpc-11	"	1.4	1.7	6.9	—	—					X	x			X								X
TPph-1	"	0.1	0.6	9.3	—	—					X	X								x			X
TPph-2	"	0.4	0.5	9.1	—	—					X	X			x					x			X
TPph-3	"	0.6	2.2	5.8	1.4	—					X	x		x						x			X
TPph-4	"	0.5	3.0	6.5	—	—					X	x		x	X					x			X
MPc-1	Clayton	—	1.4	8.6	—	—							X				x		x	x			X
IPc-1	"	0.5	0.6	8.9	—	—					X									x			X
IPc-2	"	0.4	0.6	9.0	—	—						X		x						X			X
IPc-3	"	0.4	0.6	9.0	—	—					x	x								X			X
IPc-4	"	0.4	0.4	9.2	—	—					x		x	x					x	X			X
IPc-5	"	1.3	1.4	7.3	—	—					x									x			X
IPc-6	"	0.7	0.9	8.4	—	—					x	x								X			X
IPc-8	"	1.2	0.5	8.3	—	—						x								x			X
IPc-9	"	1.0	0.6	8.4	—	—					x									X			X
IPc-10	"	1.2	0.8	8.0	—	—					X	x	x				x		x	x			X
IPc-11	"	1.0	0.9	8.1	—	—					x	X			x					x			X
IPc-12	"	1.0	0.6	8.4	—	—						x		x						X			X
IPc-13	"	0.1	1.3	8.6	—	—					X	x	x						x	x			X
IPc-14	"	1.5	1.1	7.4	—	—					x	x		x						X			X
IPc-15	"	1.1	2.3	6.6	—	—					x			x						x			X
IPc-16	"	1.0	1.1	7.9	—	—						x	x	x						X			X
IPc-17	"	1.2	0.6	8.2	—	—					X				x					X			X
KPpc-1	"	2.1	1.3	6.6	—	—						x		x	x		X		x	X		X	
KPpc-2	"	0.6	1.6	7.8	—	—					X	X	x							X			X
TPcj-1	"	—	0.9	9.1	—	—					X		x		X			x	x				X
TPch-1	"	1.0	5.4	1.8	1.8	—					x		x	x	X	X	X	X	X	X		X	
MKo-1	Owl Creek	0.7	1.5	7.8	—	—									x				x	x			X
MKo-4	"	0.7	1.1	8.2	—	—														x			X

TABLE 1.—*Continued*

Sample	Formation	Clay mineralogy (parts in ten)					Environmental criteria													Environmental interpretations		
		Kaolinite	Illite	Montmorillonite	Mixed lattice	Chlorite	Lignite beds	Leaf fossils	Fluvial-type sands	Cut-and-fill	Radiolaria	Hystrichosphieridae	Planktonic Foraminifera	Fish scales and teeth	Mollusca	Ostracodes	Benthonic Foraminifera	Shell fragments	Carbonate	Glauconite	Fluviatile	Inner neritic	Outer neritic
MKo-5	Owl Creek	0.7	1.1	8.2	—	—														x			X
MKo-6	"	0.7	1.1	8.2	—	—														x			X
MKo-7	"	0.7	1.1	8.2	—	—														x			X
MKo-8	"	0.7	1.1	8.2	—	—														x			X
MKo-9	"	0.7	1.1	8.2	—	—														x			X
MKo-10	"	0.7	1.1	8.2	—	—														x			X
MKo-11	"	0.7	1.1	8.2	—	—														x			X
MKo-12	"	0.7	1.1	8.2	—	—														x			X
MKo-13	"	0.7	1.1	8.2	—	—														x			X
MKo-14	"	0.7	1.1	8.2	—	—														x			X
MKo-15	"	0.7	1.1	8.2	—	—														x			X
MKo-16	"	0.7	1.1	8.2	—	—														x			X
MKo-17	"	0.7	1.1	8.2	—	—														x			X
MKo-18	"	0.7	1.1	8.2	—	—														x			X
MKo-19	"	0.7	1.1	8.2	—	—														x			X
MKo-20	"	0.7	1.1	8.2	—	—														x			X
MKo-21	"	0.7	1.1	8.2	—	—														x			X
MKo-22	"	0.7	1.1	8.2	—	—														x			X
MKo-23	"	0.7	1.1	8.2	—	—														x			X
MKo-24	"	0.7	1.1	8.2	—	—														x			X
MKo-25	"	0.7	1.1	8.2	—	—														x			X
MKo-26	"	0.7	1.1	8.2	—	—														x			X
MKo-27	"	0.7	1.1	8.2	—	—														x			X
MKo-28	"	0.7	1.1	8.2	—	—														x			X
MKo-29	"	0.7	1.1	8.2	—	—														x			X
MKo-30	"	0.7	1.1	8.2	—	—														x			X
MKo-31	"	0.7	1.1	8.2	—	—														x			X
MKo-32	"	0.7	1.1	8.2	—	—														x			X
MKo-33	"	0.7	1.1	8.2	—	—														x			X
MKo-34	"	0.7	1.1	8.2	—	—														x			X
MKo-35	"	0.7	1.1	8.2	—	—														x			X
MKo-36	"	0.7	1.1	8.2	—	—														x			X
MKo-37	"	0.7	1.1	8.2	—	—														x			X
MKo-38	"	0.7	1.1	8.2	—	—														x			X
MKo-39	"	0.7	1.1	8.2	—	—														x			X
MKo-40	"	0.7	1.1	8.2	—	—														x			X
MKo-41	"	0.7	1.1	8.2	—	—														x			X
MKo-42	"	0.7	1.1	8.2	—	—														x			X
MKo-43	"	0.7	1.1	8.2	—	—														x			X
MKo-44	"	0.7	1.1	8.2	—	—														x			X
MKo-45	"	0.7	1.1	8.2	—	—														x			X
MKo-46	"	0.7	1.1	8.2	—	—														x			X
MKo-47	"	0.7	1.1	8.2	—	—														x			X
MKo-48	"	0.7	1.1	8.2	—	—														x			X
MKo-49	"	0.7	1.1	8.2	—	—														x			X
MKo-50	"	0.7	1.1	8.2	—	—														x			X
MKo-51	"	0.7	1.1	8.2	—	—														x			X
MKo-52	"	0.7	1.1	8.2	—	—														x			X
MKo-53	"	0.7	1.1	8.2	—	—														x			X
MKo-54	"	0.7	1.1	8.2	—	—														x			X
MKo-55	"	0.7	1.1	8.2	—	—														x			X
MKo-56	"	0.7	1.1	8.2	—	—														x			X
MKo-57	"	0.7	1.1	8.2	—	—														x			X
MKo-58	"	0.7	1.1	8.2	—	—														x			X
MKo-59	"	0.7	1.1	8.2	—	—														x			X
MKo-60	"	0.7	1.1	8.2	—	—														x			X
MKo-61	"	0.7	1.1	8.2	—	—														x			X
MKo-62	"	0.7	1.1	8.2	—	—														x			X
MKo-63	"	0.7	1.1	8.2	—	—														x			X
MKo-64	"	0.7	1.1	8.2	—	—														x			X
MKo-65	"	0.7	1.1	8.2	—	—														x			X
MKo-66	"	0.7	1.1	8.2	—	—														x			X
MKo-67	"	0.7	1.1	8.2	—	—														x			X
MKo-68	"	0.7	1.1	8.2	—	—														x			X
MKo-69	"	0.7	1.1	8.2	—	—														x			X
MKo-70	"	0.7	1.1	8.2	—	—														x			X
MKo-71	"	0.7	1.1	8.2	—	—														x			X
MKo-72	"	0.7	1.1	8.2	—	—														x			X
MKo-73	"	0.7	1.1	8.2	—	—														x			X
MKo-74	"	0.7	1.1	8.2	—	—														x			X
MKo-75	"	0.7	1.1	8.2	—	—														x			X
MKo-76	"	0.7	1.1	8.2	—	—														x			X
MKo-77	"	0.7	1.1	8.2	—	—														x			X
MKo-78	"	0.7	1.1	8.2	—	—														x			X
MKo-79	"	0.7	1.1	8.2	—	—														x			X
MKo-80	"	0.7	1.1	8.2	—	—														x			X
MKo-81	"	0.7	1.1	8.2	—	—														x			X
MKo-82	"	0.7	1.1	8.2	—	—														x			X
MKo-83	"	0.7	1.1	8.2	—	—														x			X
MKo-84	"	0.7	1.1	8.2	—	—														x			X
MKo-85	"	0.7	1.1	8.2	—	—														x			X
MKo-86	"	0.7	1.1	8.2	—	—														x			X
MKo-87	"	0.7	1.1	8.2	—	—														x			X
MKo-88	"	0.7	1.1	8.2	—	—														x			X
MKo-89	"	0.7	1.1	8.2	—	—														x			X
MKo-90	"	0.7	1.1	8.2	—	—														x			X
MKo-91	"	0.7	1.1	8.2	—	—														x			X
MKo-92	"	0.7	1.1	8.2	—	—														x			X
MKo-93	"	0.7	1.1	8.2	—	—														x			X
MKo-94	"	0.7	1.1	8.2	—	—														x			X
MKo-95	"	0.7	1.1	8.2	—	—														x			X
MKo-96	"	0.7	1.1	8.2	—	—														x			X
MKo-97	"	0.7	1.1	8.2	—	—														x			X
MKo-98	"	0.7	1.1	8.2	—	—														x			X
MKo-99	"	0.7	1.1	8.2	—	—														x			X
MKo-100	"	0.7	1.1	8.2	—	—														x			X

TABLE 1.—*Continued*

Sample	Formation	Clay mineralogy (parts in ten)					Environmental criteria														Environmental interpretations		
		Kaolinite	Illite	Montmorillonite	Mixed lattice	Chlorite	Lignite beds	Leaf fossils	Fluvial-type sands	Cut-and-fill	Radiolaria	Hystrichospheridae	Planktonic Foraminifera	Fish scales and teeth	Mollusca	Ostracodes	Benthonic Foraminifera	Shell fragments	Carbonate	Glauconite	Fluviatile	Inner neritic	Outer neritic
MKo-6	"	0.7	0.7	8.6	—	—							X	x	X		x		X	X			X
IKo-1	"	0.4	0.4	9.2	—	—								x	x					x			X
IKo-2	"	1.2	0.6	8.2	—	—														x			X
IKo-3	"	1.2	1.0	7.8	—	—							X				x			x			X
IKo-4	"	1.4	0.9	7.7	—	—														x			X
IKo-5	"	1.8	2.0	6.2	—	—									x								X
IKo-6	"	0.7	0.4	8.9	—	—								x	x					x			X
IKo-7	"	2.3	2.3	5.4	—	—								x						x			X
IKo-8	"	2.0	2.4	5.6	—	—							x							x			X
IKo-9	"	1.2	1.5	7.3	—	—								x	x					x			X
IKo-10	"	0.9	2.5	6.6	—	—						x								x			X
IKo-11	"	1.3	1.3	7.4	—	—														x			X
TKo-1	"	2.4	3.4	4.2	—	—							x		X	x	X	X	x	X		X	
TKo- 2*	"	0.7	1.5	7.8	—	—							X				x			x			X
9	McNairy	8.4	0.1	1.5	Tr.	—		x		X	x										X		
13	"	5.6	4.4	—	Tr.	—				X	X										X		
15	"	0.8	3.0	4.0	2.2	—									x					X		X	
16	"	—	3.2	Tr.	6.8	—								x	x					X		X	
29	"	5.6	3.7	0.7	Tr.	—		x		X											X		
30	"	8.8	1.2	—	Tr.	—				X	x										X		
35	"	5.6	2.8	1.6	—	—				X	x										X		
37	"	6.0	4.0	—	Tr.	—				X											X		
39	"	6.5	3.5	Tr.	—	—		x		X	x										X		
40	"	7.3	2.3	0.4	—	—				X	x										X		
41	"	7.6	1.8	0.6	—	—				X	x										X		
42	"	5.8	4.0	0.2	Tr.	—		x		X											X		
43	"	4.9	4.4	0.7	Tr.	—	X	X		x											X		
44	"	4.5	4.7	0.8	—	—	X	X		x											X		
45	"	4.0	4.3	1.7	—	—				X	x										X		
46	"	4.0	6.0	Tr.	—	—		x		X	x										X		
64	"	1.5	8.5	Tr.	—	—															X		
65	"	9.4	0.6	—	—	—															X		
74	"	2.2	1.5	6.3	—	—	X	X		x											X		
75	"	4.4	2.8	2.8	—	—	x	X		x											X		
76	"	6.6	2.7	0.7	Tr.	—				X	x										X		
81	"	8.6	1.0	0.4	—	—				X											X		
83	"	7.8	1.4	0.8	Tr.	—				X											X		
85	"	7.1	1.0	0.6	1.3	—		x		X	x										X		
87	"	8.5	1.3	0.2	Tr.	—				X	x										X		
88	"	7.2	2.6	0.2	Tr.	—	x	x													X		
89	"	9.0	0.7	0.2	Tr.	—		x		X	x										X		

TABLE 1.—*Continued*

Sample	Formation	Clay mineralogy (parts in ten)					Environmental criteria														Environmental interpretations		
		Kaolinite	Illite	Montmorillonite	Mixed lattice	Chlorite	Lignite beds	Leaf fossils	Fluvial-type sands	Cut-and-fill	Radiolaria	Hystrichosphaeridae	Planktonic Foraminifera	Fish scales and teeth	Mollusca	Ostracodes	Benthonic Foraminifera	Shell fragments	Carbonate	Glauconite	Fluviatile	Inner neritic	Outer neritic
90	"	9.4	0.6	Tr.	Tr.	—			X												X		
91	"	9.6	0.6	0.2	Tr.	—		x	X	x											X		
96	"	3.2	1.5	5.3	—	—			X	x											X		
100	"	8.6	0.8	0.3	0.3	—			X	x											X		
103	"	8.1	1.7	0.2	Tr.	—		x	X												X		
106	"	8.6	0.5	0.9	Tr.	—			X	x											X		
112	"	9.3	0.5	0.2	Tr.	—			X												X		
114	"	7.6	2.1	0.3	Tr.	—		x	X												X		
115	"	8.9	0.7	0.4	Tr.	—			X	x											X		
116	"	9.0	0.7	0.3	Tr.	—		x	X												X		
117	"	8.9	0.9	0.2	Tr.	—		x	X	x											X		
122*	"	3.9	4.3	1.8	Tr.	Tr.	x	x													X		
123*	"	4.5	4.1	1.4	Tr.	Tr.	x	x													X		
125	"	9.5	0.2	0.3	Tr.	—			X	x											X		
129	"	9.5	0.5	—	—	—		x	X												X		
133	"	8.5	1.1	0.4	Tr.	—		x	X												X		
135	"	8.1	1.2	0.7	Tr.	—		x	X												X		
142	"	9.1	0.3	0.6	Tr.	—			X												X		
143	"	9.1	0.6	0.3	Tr.	—	x	x	X	x											X		
144	"	8.7	1.0	0.3	Tr.	—			X												X		
145	"	9.1	0.9	—	—	—		x	X	x											X		
148	"	8.5	1.5	—	—	—			X	x											X		
150	"	7.5	2.0	0.5	Tr.	—		x	X												X		
153	"	7.1	2.3	0.6	Tr.	—		x	X												X		
154	"	8.9	0.9	0.2	Tr.	—			X	x											X		
155	"	6.8	2.7	0.5	Tr.	—		x	X												X		
160	"	9.4	0.6	—	—	—		x	X												X		
161	"	9.2	0.8	—	—	—			X	x											X		
168	"	8.7	0.8	0.5	Tr.	—		X	x												X		
169	"	9.2	0.8	—	—	—	x	x	X												X		
172	"	8.4	1.6	—	—	—			X												X		
174	"	8.9	1.1	Tr.	Tr.	—			X												X		
178	"	8.7	1.0	0.3	Tr.	—			X												X		
180	"	7.7	2.3	Tr.	—	—			X												X		
188	"	8.8	1.2	—	—	—			X												X		
190	"	8.1	1.9	—	Tr.	—			X												X		
199	"	5.8	4.2	—	Tr.	—			X												X		
201	"	6.2	2.0	1.8	Tr.	—			X												X		
210	"	4.9	5.1	—	Tr.	—	x	x	X												X		
211	"	7.6	2.4	—	Tr.	—	x	x	X	x											X		
212	"	8.5	1.5	Tr.	Tr.	—			X												X		

TABLE 1.—*Continued*

TABLE 1.—*Continued*

Sample	Formation	Clay mineralogy (parts in ten)					Environmental criteria														Environmental interpretations		
		Kaolinite	Illite	Montmorillonite	Mixed lattice	Chlorite	Lignite beds	Leaf fossils	Fluvial-type sands	Cut-and-fill	Radiolaria	Hystrichospheridae	Planktonic Foraminifera	Fish scales and teeth	Mollusca	Ostracodes	Benthonic Foraminifera	Shell fragments	Carbonate	Glauconite	Fluviatile	Inner neritic	Outer neritic
215	Coon Creek	3.5	3.9	1.3	1.3	—							x		x		x	x	x	x		X	
216	"	3.6	4.0	2.4	—	—									x					x		X	
217	"	7.3	2.0	0.7	Tr.	—									x					X		X	
218	"	3.7	2.9	3.4	Tr.	Tr.																X	
219	"	2.6	5.2	2.2	Tr.	—							x		X	x	x	X	x	x		X	
220	"	2.4	0.5	7.1	Tr.	Tr.							x	x	x	x	x	X	x	x		X	
221	"	4.2	4.4	1.4	Tr.	Tr.		x							X	x	X			X		X	
222	"	2.8	3.3	3.9	Tr.	—									X	x	X	x		X		X	
223	"	1.7	1.2	7.1	Tr.	Tr.							x		X	x	X	X	x	X		X	
224	"	1.5	1.0	7.5	—	—									X	x	X	x	x	X		X	
225	"	3.4	4.7	1.9	Tr.	—									X		X	x	x	X		X	
226	Selma	3.0	3.1	3.9	—	—							X		X	x	x	X	x	x			X
227	"	1.1	1.3	7.6	—	—							X		X	x	x	X	x	x			X
228	"	1.6	1.7	6.7	—	—							X		x		x	X	x	x		X	
229*	"	3.1	4.1	2.8	Tr.	—							X			x	X			x		X	
230*	"	4.2	3.4	2.4	Tr.	Tr.							x			x	X		X	x			X
231*	"	2.0	0.6	7.4	—	Tr.							X				x		X	x			X
232	"	1.6	3.2	5.2	Tr.	—							X		x	x	x	X	X	x			X
233	"	1.2	0.4	8.4	—	—							X		x		x	X	X	X			X
234	"	1.8	1.8	6.4	—	—							X		x		x	X	X	x			
TKc-1	Coffee	2.3	6.6	1.1	—	—	X	X	X	X											X		
TKc-2	"	1.7	Tr.	8.3	Tr.	—		x												x		X	
TKc-3	"	3.3	4.9	1.8	Tr.	—	X	X	x	x												X	
TKc-4	"	4.8	0.4	4.8	Tr.	—		x	x													X	
TKc-5	"	6.3	2.7	1.0	—	Tr.		x	x	x												X	
TKc-6	"	3.9	5.0	1.1	Tr.	Tr.	X	X		x												X	
TKc-7	"	7.0	0.8	2.2	—	—	X	X	X	X												X	
IKt-1	Tuscaloosa	1.9	8.1	—	Tr.	—			x	X												X	
IKt-2	"	4.3	5.7	—	Tr.	—	x			x												X	
IKt-3	"	3.5	6.5	—	Tr.	—	x			x												X	
IKt-4	"	4.7	4.0	1.3	Tr.	—	x			x												X	
IKt-5	"	6.4	0.8	2.8	Tr.	—	x			x												X	
IKt-6	"	6.0	1.2	2.8	Tr.	—	x			x												X	
IKt-7	"	5.5	2.9	1.6	Tr.	—	x			x												X	
IKt-8	"	2.2	7.8	Tr.	Tr.	—	x			x												X	
IKt-9	"	8.7	0.2	1.1	—	—	x			x												X	
KKt-1	"	7.5	1.4	1.1	Tr.	—			x	x												X	
KKt-2	"	8.2	1.8	—	Tr.	—		x	x	x												X	
TKt-1	"	10.0	—	—	Tr.	—																	

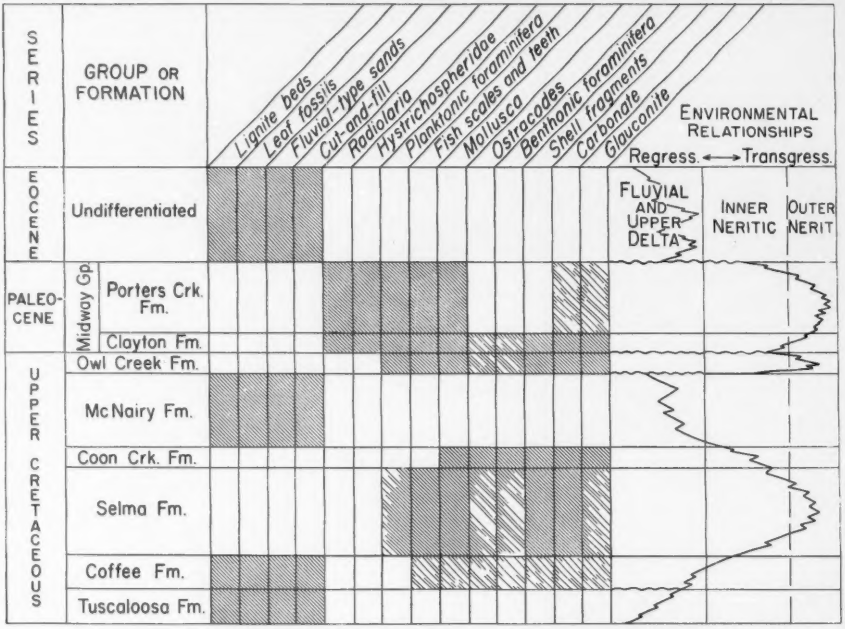

FIG. 3.—Criteria observed and interpretations of environments for the stratigraphic units.

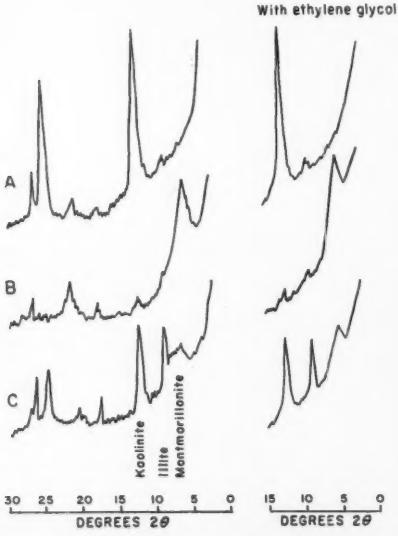

FIG. 4.—X-ray spectrometer patterns (Cu radiation) of clay fractions showing the three typical clay mineral associations: (A) kaolinite, (B) montmorillonite, (C) kaolinite-illite-montmorillonite.

grams with the three end points represented by kaolinite, illite, and montmorillonite. Table 2 shows the average clay mineral compositions of the various stratigraphic units.

The clays of the Eocene (undifferentiated) formations and of the Cretaceous McNairy and Tuscaloosa Formations and the northern part of the Coffee Formation are dominantly kaolinite with varying amounts of illite and generally small amounts of montmorillonite. The clays of the Porters Creek, Clayton, and Owl Creek Formations and the southern part of the Selma Formations are dominantly montmorillonite with small amounts of illite and kaolinite. The clays of the Coon Creek Formation, the northern

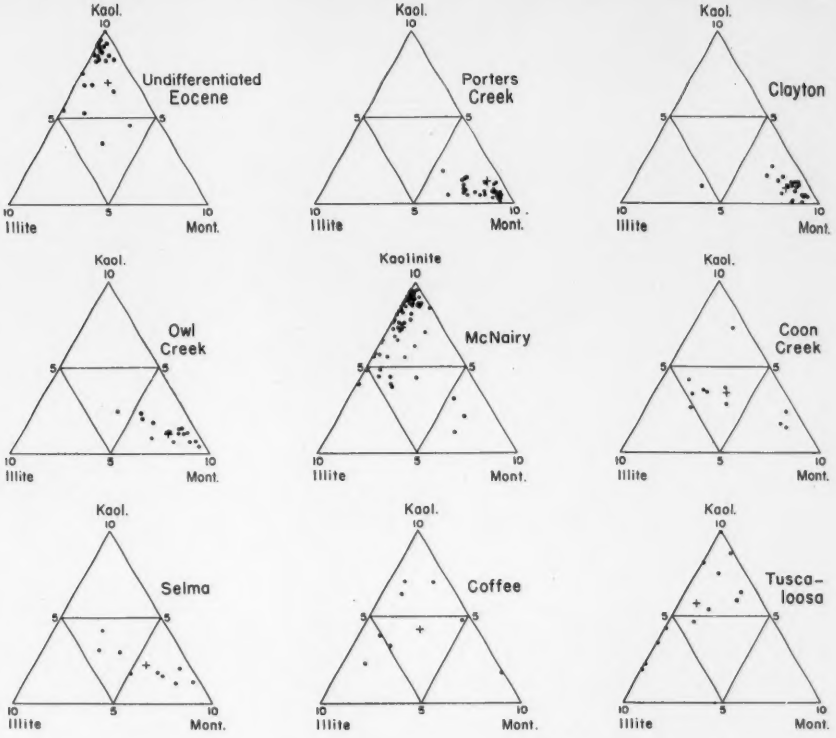

FIG. 5.—Clay mineral compositions plotted by stratigraphic unit. The average composition of each unit (table 3) is shown by (+).

TABLE 2.—*Average clay mineral compositions of the stratigraphic units*

Stratigraphic unit	Number of samples	Clay Minerals (parts in ten)		
		Kaolinite	Illite	Montmorillonite
Eocene (undifferentiated)	28	7.0	1.4	1.6
Paleocene				
Porters Creek	27	0.7	1.2	8.1
Clayton	21	0.9	1.2	7.9
Cretaceous				
Owl Creek	16	1.2	1.5	7.3
McNairy	68	7.3	2.1	0.6
Coon Creek	11	3.4	3.0	3.6
Selma	9	2.2	2.2	5.6
Coffee	7	4.2	2.9	2.9
Tuscaloosa	12	5.7	3.4	0.9

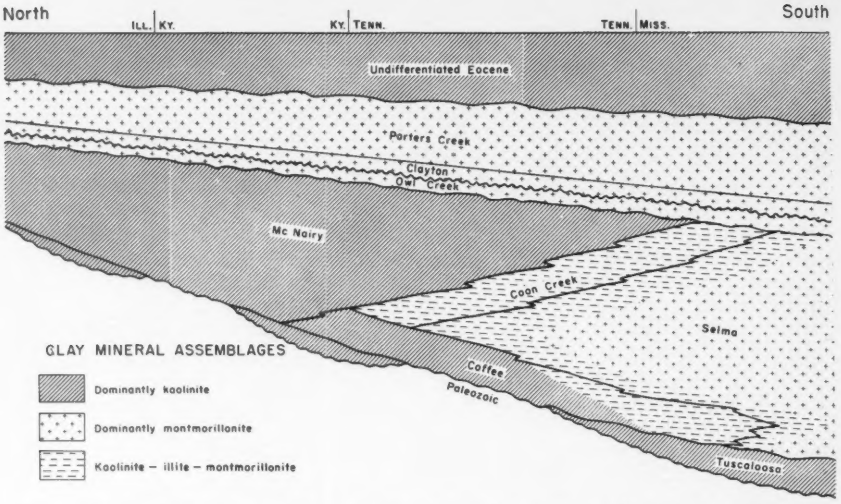

FIG. 6.—Generalized north-south cross section showing facies relationships of clay mineral assemblages and stratigraphic units. Section is approximately 300 miles in length.

part of the Selma Formation, and the southern part of the Coffee Formation contain nearly equal amounts of kaolinite, illite, and montmorillonite.

Figure 6 is a generalized north-south cross section of the Upper Mississippi Embayment showing the stratigraphic aspects of the various units. The three general clay mineral assemblages are superimposed (fig. 4) on the cross section illustrating the general clay mineral facies and stratigraphic relationships. The kaolinite facies are found in the undifferentiated Eocene Series, the McNairy Formation, the northern part of the Coffee Formation, and the Tuscaloosa Formation. The montmorillonite facies are found in the Porters Creek Formation, the Clayton Formation, the Owl Creek Formation, and the southern part of the Selma Formation. The kaolinite-illite-montmorillonite facies are found in the Coon Creek Formation, the northern part of the Selma Formation, and the southern part of the Coffee Formation.

Clay Mineral Composition and Environment

The clay mineral data and the environmental interpretations for each sample (table 1) are summarized in figure 7, and table 3 gives the average clay mineral composition of clays from the three environments.

TABLE 3.—*Average clay mineral composition of clays from the three environments*

Environment	Number of samples	Kaolinite	Illite	Montmorillonite
Fluviatile	112	6.9	1.9	1.2
Inner Neritic	19	3.1	3.1	3.8
Outer Neritic	68	0.9	1.3	7.8

Clays deposited in the fluviatile environment are dominantly kaolinite, clays deposited in the outer neritic environment are dominantly montmorillonite, and clays deposited in the inner neritic environment are nearly equal mixtures of the three components.

The three clay mineral facies depicted in figure 6 represent the environments of deposition plotted in figure 7. Clays from the undifferentiated Eocene, the McNairy Formation, the northern part of the Coffee Formation, and the Tuscaloosa Formation were in general deposited in the fluviatile environment. Clays from the Porters Creek Formation, the Owl Creek Formation, and

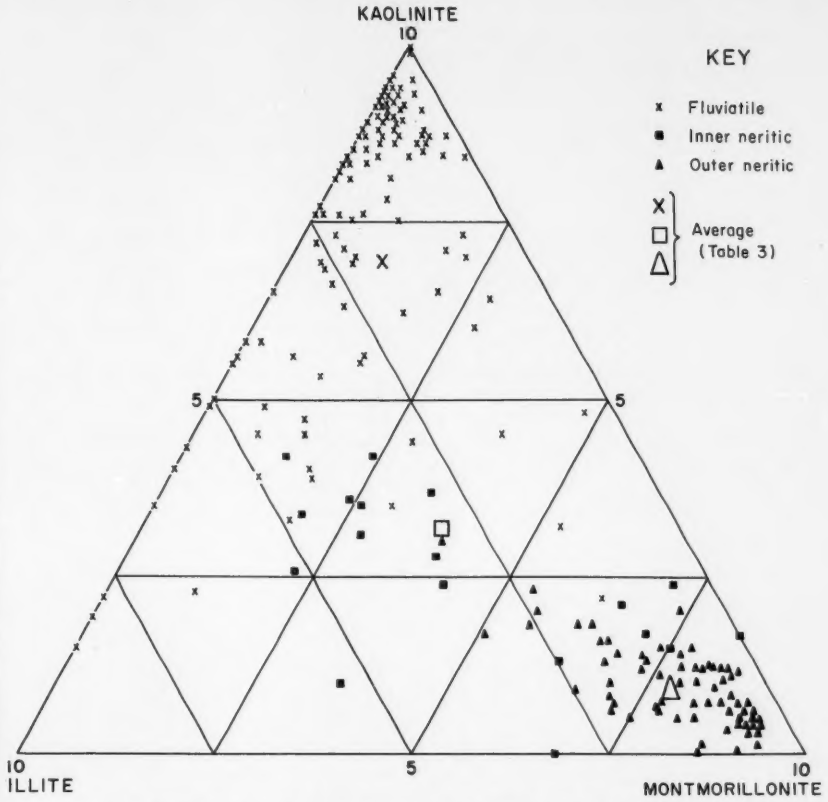

FIG. 7.—Clay mineral compositions plotted showing the relation between clay mineralogy and depositional environments.

the southern part of the Selma Formation were deposited in the marine outer neritic environment. Clays from the Clayton Formation, the Coon Creek, the northern part of the Selma Formation, and the southern part of the Coffee Formation were deposited in the transitional marine inner neritic environment.

DISCUSSION

Kaolinite, illite, and montmorillonite are the three main types of clay minerals present in the sediments of the Upper Mississippi Embayment. These minerals do not occur as random mixtures throughout the geologic section but have a definite pattern of assemblage and occurrence (fig. 5).

What are the factors that influence the clay minerals present in a series of sediments? Keller (1956, p. 2690) showed the two main factors are source area and depositional area. The part each plays in the final association depends upon the interplay of the two. Weaver (1958, p. 258) concluded that clay minerals in sedimentary rocks are chiefly detrital in origin, strongly reflect the character of their source material, and are only slightly modified by their depositional environments.

Studies of the provenance of the upper Cretaceous (Pryor, 1960) and Tertiary (Grim, 1936; Potter and Pryor, in preparation) sediments of the Upper Mississippi Embayment show that the Blue Ridge

and Piedmont Plateau region was the most probable source area for the sediments and did not change significantly in character throughout Cretaceous and Tertiary time. Therefore, changes in source area and change in climatic conditions of the source area cannot be considered important causes of clay mineral variations. Factors imposed at the depositional site would thus seem to be the determining ones.

What are the influences of the depositional site that may affect the clay minerals deposited there? Marine diagenesis is perhaps the factor most frequently used to explain variations in clay mineralogy. Grim and his co-workers (1949, 1955, 1956) concluded that diagenetic changes were the most important factors in clay mineral distribution. Grim and Johns (1958, p. 198), however, on the basis of work in the Mississippi Delta area, concluded that diagenesis was of much less importance than would have been expected in the light of their earlier studies.

Montmorillonite, supposedly the most readily altered of all clay minerals in a marine environment, occurs in large quantities in the marine Porters Creek, Clayton, Owl Creek, and Coon Creek Formations and the southern part of the Selma Formations. If diagenesis had not markedly affected montmorillonite it could hardly be expected to have altered the much more stable kaolinite and muscovite-crystallization illite. The only clay mineral that appears to have been primarily the result of diagenesis is glauconite. Therefore, kaolinite, illite, and montmorillonite are considered as detrital particles transported from the source area and deposited in the Mississippi Embayment with little if any diagenetic change.

The possibility arises that the large amounts of montmorillonite present may be the result of alteration from volcanic ash. If ash falls were responsible, montmorillonite should be found in large quantities in fluviatile sediments as well as in marine sediments. This has not been observed. Moreover, volcanic shards should in such case be a common constituent of montmorillonitic sediments derived from ash, but shards seldom have been observed. Undoubtedly some ash fell in the embayment as the result of late Cretaceous and Tertiary volcanism, but the amount is considered insignificant.

If changing source area, significant climatic changes, diagenesis, and volcanism are of relative unimportance in the differentiation of the clay minerals, segregation in the depositional environments appears as the most significant factor.

If diagenesis is considered a physiochemical mechanism, segregation is chiefly a physical one. The mechanisms responsible for this segregation can be summarized as (1) differential settling of the clay particles owing to differences in particle size, (2) differences in flocculation rate, and (3) differences in floccule size.

Montmorillonite generally occurs in much smaller particle sizes than either kaolinite or illite and will be kept in suspension by a much weaker agitation. Consequently, kaolinite and illite will settle out first whereas montmorillonite may be transported farther from shore, away from wave-agitated areas.

Differences in rate of flocculation occur in response to the salinity of the water. Whitehouse (1952) and Whitehouse and Jeffrey (1955) have demonstrated that kaolinite and illite form large floccules immediately upon entering waters of relatively low salinities whereas montmorillonite flocculates at only high salinities and then only slowly. Moreover, the floccules of montmorillonite seldom attain the size of those of the kaolinite and illite.

Such clay mineral-environmental association is not peculiar to the Cretaceous and Tertiary sediments of the Mississippi Embayment. Groot and Glass (1960) recently have applied this interpretation to the Cretaceous and Tertiary clays of the northern Atlantic Coastal Plain and have shown that the nonmarine lower Cretaceous clays are composed chiefly of kaolinite, and the marine upper Cretaceous and marine Tertiary clays have a montmorillonite-kaolinite-illite-chlorite association in the inner neritic environments. Van Andel and Postma (1954, p. 78–79) have shown the clays of the delta in the Gulf of Paria to be an illite-kaolinite association and the offshore marine clays to be a montmorillonite-kaolinite association. Weaver (1958, p. 258–259) points out that in ancient sediments kaolinite is most abundant in con-

tinental and nearshore sediments and that montmorillonite is most commonly found in marine sediments.

Segregation of clay minerals in the depositional environment probably is more common than is generally recognized and should be the expected process in relatively young, unconsolidated materials in which the factors of time, intrastratal solution, and consolidation have not favored diagenesis. However, segregation of clay minerals in depositional environments should not be used as the solution to all environmental interpretations. The Mississippi Embayment is perhaps an ideal example because there the factors of source area, climate, and diagenesis are minor in relation to the segregation factors within the environments. Weaver (1958, p. 258) justifiably has pointed out that there is no over-all consistent coincidence between clay minerals and depositional environments and that specific clay minerals in a specific basin of deposition strongly reflect the character of the source material.

The provenance factors of a suite of sediments must be determined before any environmental implications can be drawn from clay mineral associations in the depositional area. Environmental interpretations must not be made on the basis of clay mineral composition alone.

Keller (1956, p. 2690) also cautioned against the promiscuous use of clay minerals alone as indicators of source area environments. It would be unwise to make source area interpretations without a full understanding of provenance features other than clay mineral distribution.

If clay minerals are to be used as indicators to interpret source area and depositional environments, a detailed and integrated stratigraphic-paleontologic-petrologic investigation should precede the clay mineral investigation in order to ascertain the importance of the role played by major variables, (1) source area multiplicity, (2) source area composition, (3) source area climate, (4) depositional environment, and (5) the magnitude of diagenetic changes.

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FIGS. 1–2, MARCH, 1961

HEAVY MINERALS OF THE MIOCENE HARRISON FORMATION IN NORTHWESTERN NEBRASKA[1]

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ABSTRACT

The heavy minerals identified in this study indicate that the sediments of the Harrison Formation were derived from mixed sources and from reworked sediments originally deposited west of the study area. Easily weathered unstable minerals are rare or absent. No significant heavy mineral zonations of the Harrison Formation are evident from this study.

Daemonelix forms were found in the lower portion of the Harrison Formation at its type locality where they have heretofore been recognized only in the upper portion of the formation.

The use of bromoform facilitates heavy mineral separation because it is easily frozen, and heavy mineral concentrations can be readily trapped by freezing the lower end of a test tube in which the separation has been made. The floating light minerals and unfrozen bromoform can be decanted, leaving a clean heavy mineral concentrate.

INTRODUCTION

Purpose of Investigation

The objective of this study is a detailed petrographic analysis of the heavy minerals of the Harrison Formation in northwestern Nebraska, directed toward determining whether or not zonations based on the types and relative abundances of these minerals can be established. An effort is made to determine what mineral provenance or provenances have contributed to the sediments of the Harrison Formation.

Seven exposures of the Harrison Formation in Sioux, Dawes, and Scotts Bluff Counties were measured and sampled for the study. Field work was carried out during and following the University of Nebraska Summer Field Camp in the summer of 1954. Laboratory study and compilation of the data was done during the academic year 1954–55.

Previous Work

Interest in the Harrison Formation of Miocene age and related Tertiary beds was stimulated at an early date by the discovery of vertebrate fossils in the study area. Members of the Owen party explored portions of the Badlands, and Owen (1852) includes in his report Leidy's descriptions of the fossil mammals and reptiles collected in the "Mauvaises Terres" of Nebraska.

Hayden (1869, 1872) proposed a tentative classification of the Tertiary in the northern Great Plains, and Darton (1899, 1903, 1905) proposed essentially the classification still in use. Darton applied the names Arikaree and Gering Formations to the Miocene beds. Hatcher (1902) suggested that the Arikaree be divided into two units, the Monroe Creek and Harrison Formations. The so-called "Upper" Harrison beds of Hatcher's Harrison Formation are now designated the Marsland Formation (Schultz, 1938).

A. L. Lugn (1939) published a comprehensive paper on the history of the various classifications of the Tertiary in Nebraska in an effort to rid the system of ambiguities. Lugn (1938, 1939) elevated Darton's Arikaree Formation to the rank of a group, which now consists of the Gering, Monroe Creek, and the redefined Harrison Formations. He concurred in recognition of the Hemingford group, comprised of the Marsland (old "Upper" Harrison) and Sheep Creek Formations, which had been proposed by Schultz (1938).

Several theses have been written on this area; one by R. V. Lugn (1955) includes heavy mineral analyses of three sections from the Harrison Formation. Other lithologic studies of the formations above and below the Harrison have been conducted by

[1] Publication authorized by the Director, U. S. Geological Survey. Manuscript received March 28, 1960.

Burkholder (1941), Horney (1941), Heidtbrink (1949), and Svoboda (1950).

Location and Size of Area

The study area of the Harrison Formation in Sioux, Dawes, and Scotts Bluff Counties, Nebraska is in the northwestern corner of the Nebraska panhandle, being bounded on the north by South Dakota, on the west by Wyoming, and on the south and east by Banner, Morril, Box Butte, and Sheridan Counties, Nebraska (fig. 1). This area includes a portion of the Pine Ridge where the upland High Plains are capped mostly by the Harrison and Marsland Formations; locally these formations are overlain by the younger Sheep Creek and Ogallala Formations. The weathering of the Harrison forms a subdued, gently rolling topography and, in some of the more dissected portions, is characterized by craggy, massive "pipy" concretions and the unique Daemonelix features to which further reference will be made in the discussion of stratigraphy.

FIELD WORK

Seven exposures of the Harrison Formation were sampled for petrographic analysis of the heavy minerals. These exposures are: (1) the exposures at University and Carnegie Hills, east of Agate, Sioux County, in the vicinity of the famous Agate fossil quarries; (2) an outcrop immediately south of the town of Andrews, Sioux County, Nebraska; (3) the "Giant Bowling Ball" locality, north of Harrison; (4) the type locality of the Harrison Formation, also north of the town of Harrison; (5) outcrops along the ridge south of Chadron, Dawes County, near the Chadron State Park; (6) exposure in Bryan Canyon, south of Crawford, Dawes County; and (7) an exposure on Wildcat Ridge, south of the town of Mitchel, Scotts Bluff County. Prior to the collection of the samples, the physical characteristics of the Harrison Formation were studied in detail. Three sections illustrating typical Harrison lithologies are presented in figure 2.

The method of sample collection was based on the possibility that the heavy mineral content might show some zonation of the formation. It was considered that any zonation that might be established would be general in nature, and the sample collection was done in a fashion which would facilitate a general study. Channel samples were collected from the massive beds of loosely consolidated sands and from most of the prominent intervening concretionary layers; this method tends to average out minor anomalies in the concentrations of heavy minerals and thus to yield a fair representation of the sampled portion of a section. Some samples were collected also from Daemonelicies, from the Giant Bowling Ball concretions, and from other local features of particular interest.

As bulky samples are not necessary for a petrographic study, samples of moderate size, ranging from 300 to 500 gm each were taken.

LABORATORY PROCEDURE

Preparation of Samples for Heavy Mineral Separation

The samples were pulverized by mortar and pestle to break down the cementing calcium carbonate and thus facilitate the oxalic acid treatment and the separation of the desired size fractions. By sieving each sample and separating the fine and very fine sand (1/16 to $\frac{1}{4}$ mm) fraction from most of the silts, and from any coarser fraction, the most desirable fraction for petrographic inspection was obtained. Twenty-five gm of each sample were then placed in a beaker with 30 gm of crystalline oxalic acid and 300 cc of water, forming a 10 percent oxalic acid solution. A sprinkling of aluminum turnings was added to this solution to facilitate the removal of iron oxide coatings from the grains. The samples were then boiled gently for approximately 10 minutes or until the effervescence of the acid had ceased. After boiling, the supernate solution was decanted, carrying with it in the carbonate-rich samples some flocculated aluminum and calcium oxalate as well as some of the silt particles loosened by the acid.

The iron oxide coatings, when present, were loosened and removed by the aluminum-oxalic acid treatment. A base exchange appears to take place as the aluminum replaces the iron, and the iron and aluminum oxalates are decanted with the solution. In a number of cases, following the procedure outlined above, a reddish-brown iron stain

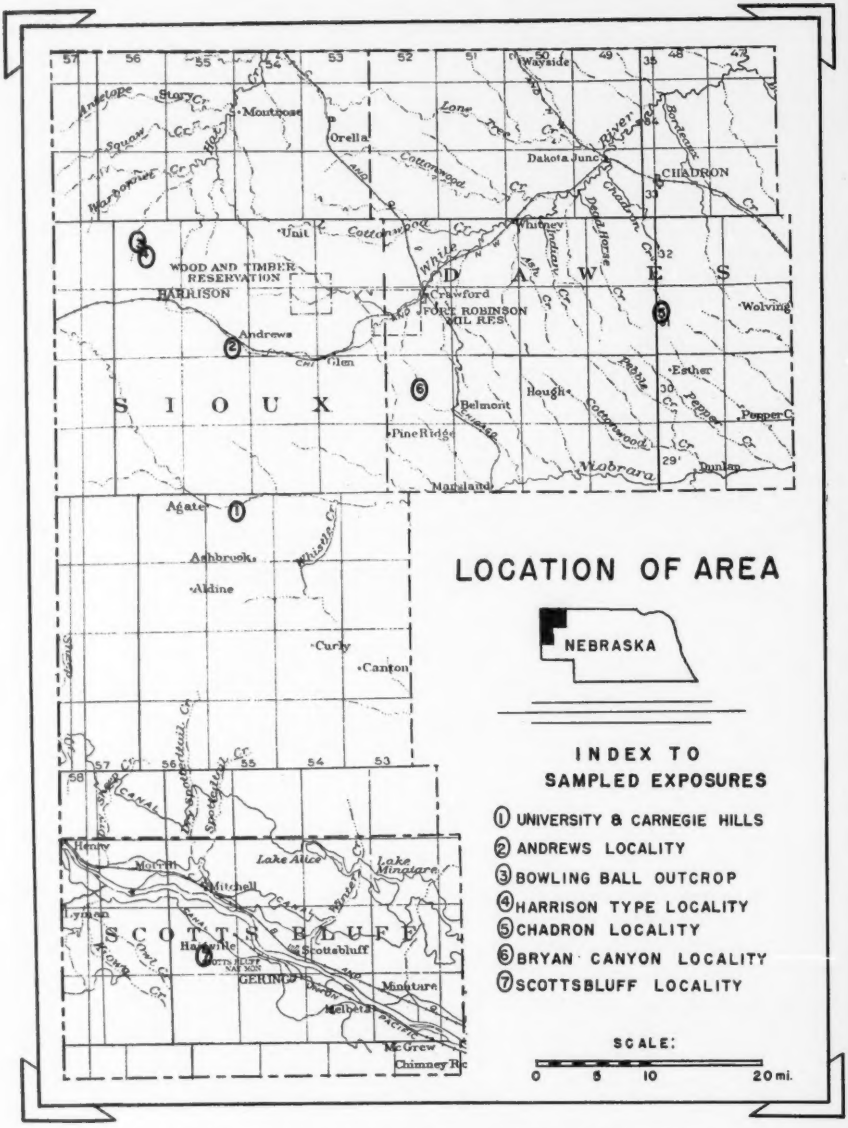

FIG. 1.—Location of area of study, showing localities sampled.

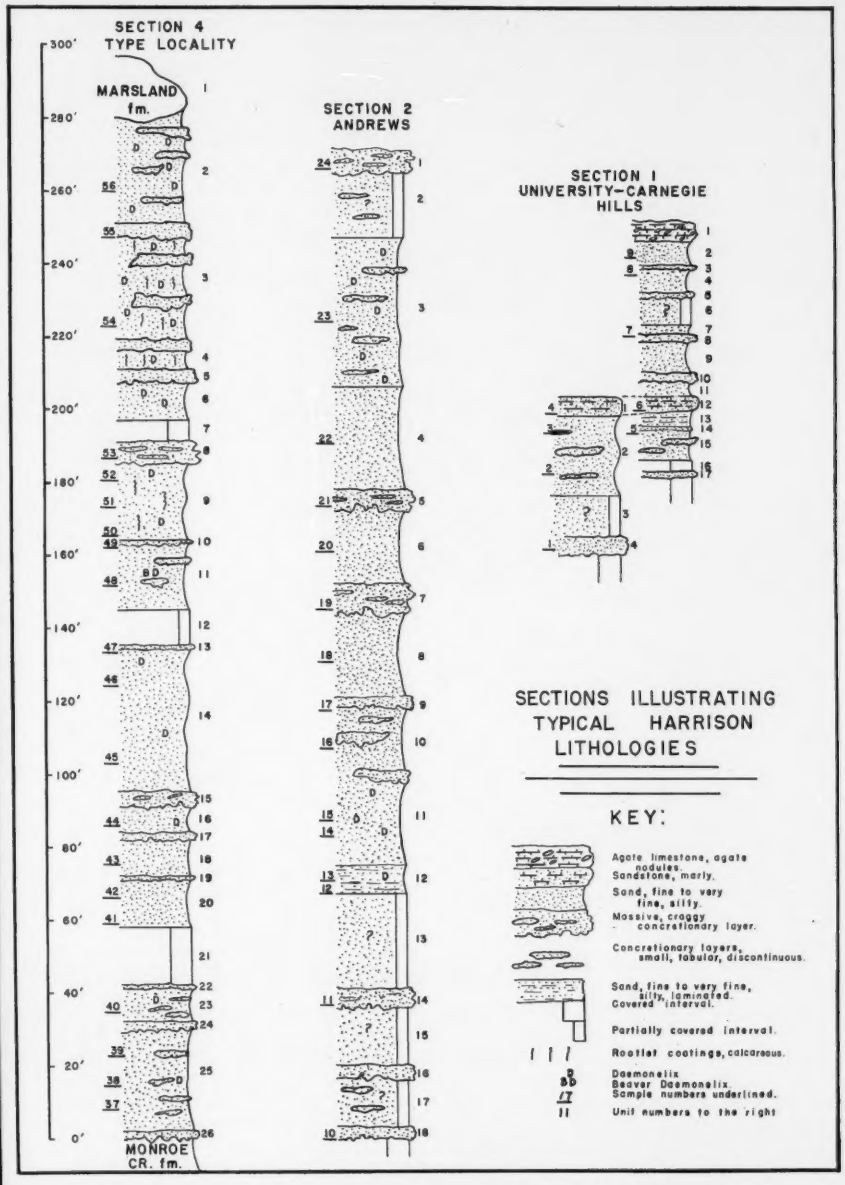

FIG. 2.—Sections illustrating typical Harrison Formation lithologies.

appeared on the aluminum filings. The remaining sample was washed with tap water two or three times or until the water remained clear when the sand settled. The samples were placed in an oven and dried at a temperature of 105° C, as suggested by Leith (1950). At this stage they still contained the aluminum filings and some silt-sized particles which had been loosened by the acid treatment, and another sieving was required to separate the clean sand fraction between 1/16 and $\frac{1}{4}$ mm. The final sieving of the samples was done with the standard Tyler sieves on a Rotap shaker. The sands were then ready for heavy mineral separation.

Heavy Mineral Separation

Bromoform was used for the heavy mineral separations. The specific gravity of bromoform is from 2.87 to 2.90, varying in proportion to the specific gravity of impurities present (Milner, 1940). In order to insure that the specific gravity was great enough for good separations, the bromoform was frozen and tested until the specific gravity was at least 2.87; some tested as high as 2.89.

Five gm of each sample were placed in centrifuge tubes. It was found that by placing the mineral grains in the tubes before adding the bromoform, the turbulent action caused by the rising of the large number of light grains resulted in a better first separation than if the mineral grains were placed in the tubes after the bromoform when two or three stirrings were necessary to achieve a complete separation. After running each centrifuge load for about 10 minutes at 1200 rpm, the cake of light minerals at the top was stirred and the centrifuging continued for another 5 minutes.

The major difficulty in separating the heavy from the light mineral grains by this method is that of preserving the separation once it has been made, and in having some assurance that there has been no contamination of the heavy mineral fraction by the light minerals. It is believed that the following process, developed by A. L. Lugn of the Department of Geology at the University of Nebraska and used by a number of his students in preparing various sands for heavy mineral studies, is more efficient than most.

Upon final removal from the centrifuge the lower portion of the tubes (that is, the portion containing the heavy minerals) was placed in an ice and salt-water mixture to freeze the lower 2 or 3 cm of the bromoform column. As the freezing temperature of bromoform is 9° C, the lower portion quickly became solid and imprisoned the heavy mineral concentrate. The light mineral fraction was then decanted into a filter paper; the unfrozen bromoform was returned to stock for future use. The light mineral fraction and the filter paper were washed with alcohol and the washings stored for future bromoform recovery. Some light mineral grains that adhered to the inside of the centrifuge tube were wiped out with a slim stirring rod wrapped in soft absorbent cloth.

After melting, bromoform containing the heavy mineral fraction was filtered and the crop of "heavies" was washed with alcohol. Both the heavy and light fractions were then stored in small vials for later study. Seventy-nine such separations were made during this study.

Preparation of Slides for Petrographic Analysis

Portions of the heavy mineral concentrates were mounted on microscope slides in Canada balsam and covered with standard cover glasses for petrographic analysis. In addition to the slides of heavy mineral grains, 4 thin sections of the material of the "Agate bed" were made and are discussed under "Physical and Lithologic Characteristics."

The remainder of the laboratory work consisted of petrographic identification of detrital minerals by standard procedures.

STRATIGRAPHY OF THE HARRISON FORMATION

Tertiary Section of Western Nebraska

The classification of the Tertiary System in Nebraska in table 1 is taken from R. V. Lugn (1955). This classification is modified after A. L. Lugn (1938, 1939) and shows revised thicknesses for some of the units reported in the earlier papers. Stratigraphic nomenclature used in this report is that of the Nebraska Geological Survey, the University of Nebraska State Museum, and the Department of Geology of the University of

TABLE 1.—*Tertiary formations of Nebraska*

Pliocene	1. Ogallala Group 300′–500′	Snake Creek channels 0′–75′
	(1) Kimball Formation 25′–50′	
	(2) Sidney Gravel Formation 15′–50′	
	(3) Ash Hollow Formation 100′–250′	
	(4) Valentine Formation 175′–225′	
	UNCONFORMITY	
Miocene	2. Hemingford Group 250′–400′	
	(1) Sheep Creek Formation 25′–200′ (Box Butte Clay may be late Sheep Creek unconformity)	
	(2) Marsland Formation 80′–200′ (old "Upper Harrison")	
	UNCONFORMITY	
	3. Arikaree Group 500′–840′	
	(1) Harrison Formation 200′–280′ (Unconformity—local)	
	(2) Monroe Creek Formation 275′–360′	
	(3) Gering Formation 80′–200′	
	UNCONFORMITY	
Oligocene	4. White River Group 500′–700′	
	(1) Brule Clay Formation 500′–600′	
	(2) Chadron Formation 50′–190′	
	UNCONFORMITY	
	Mainly Cretaceous shale Formations: Pierre, Niobrara, etc.	

Nebraska and is not necessarily that of the U. S. Geological Survey. The growth and acceptance of this classification are fully reported by A. L. Lugn (1939) and will not be discussed here.

Physical and Lithologic Characteristics

The Harrison Formation consists of fine to very fine, gray to light brownish gray silty sands with numerous massive "pipy" concretionary layers. These layers do not vary greatly in color or texture from the rest of the formation but on a weathered exposure usually appear somewhat darker than the surrounding sand. The concretions of the Harrison Formation differ from those in the other Tertiary formations of western Nebraska. They are usually more massive, being fused together by calcium carbonate cement, and on the surface weather to a craggy appearance.

A few marly limestone layers of small extent have been noted in the Harrison Formation. The contact between the Harrison and Marsland Formations is marked by a pronounced unconformity and in some localities at this horizon a highly siliceous layer occurs which has become known as the "Agate bed" because it contains small pockets of agate which locally have been commercially exploited. This layer is seen vividly in the area north and east of Agate (Agate Springs Ranch) and occurs as a resistant cap on Carnegie Hill, in which the famous Agate fossil quarries occur.

Several possible origins for this "Agate" layer have been suggested. A. L. Lugn (personal communication) suggests that it may be the result of secondary silica replacement of an algal limestone, as the structures reflect apparent algal structures. Lugn feels that the silica may have been derived from hydrated volcanic ash transported in a colloidal state and precipitated under more acid conditions than those prevailing in the zone from which the silica was derived. This action could have been facilitated by the percolation of ground water.

It is also suggested that this layer may have been formed from diatomaceous ooze or hydrated volcanic ash that was precipitated in pockets in a fresh-water pond. Dur-

ing compaction and dehydration the silica nodules were fractured and the fractures filled with calcite, resulting in what appears to be a brecciated chert cemented with calcite. (Personal communication, C. M. Riley and R. L. Threet, formerly of the Department of Geology, University of Nebraska.) What appears to be manganese dendrites occur both along the calcite seams and within the wholly silicified portions of the material.

The unique Daemonelix forms were first described by Barbour (1892) as new gigantic fossils or "Devil's Corkscrews" and offered the provisional name *Daemonelix*. Barbour further proposed that the structures were fossilized remnants of a large twisting vine which climbed using other plants or trees for support. Other investigators found fossil beaver remains in the Daemonelicies and proposed that they were remains of beaver burrows. A. L. Lugn (1941) suggests harmonizing the two principal theories of Daemonelix origin as follows:

> "Any satisfactory theory to explain the Daemonelix must account for the very impressive plant and vine resemblances of these structures, the perfectly fossilized plant cells and other minute structures preserved in them, and also for the rodent remains found in so many of them. . . . The explanation for the small vegetal material becomes apparent when it is realized that most of the wood had rotted away before the rodent found it advantageous to dig out most of the remainder and make his home in the space it had occupied."

Schultz (1942) reviews the whole Daemonelix problem. These forms have generally been thought to be confined to the upper 150 feet of the Harrison Formation. However, some forms have been found at slightly lower horizons in the type locality and the division between the upper and lower members of the Harrison Formation has been variously designated on the basis of the lowermost occurrence of the Daemonelicies. However, while sampling the type locality for this study, three Daemonelicies were found within 19 feet of the base of the formation and another 44 feet above the basal Harrison concretionary ledge.[2] Thus, though the structures are most abundantly exposed in the upper portion of the formation, they are not confined to it, as has previously been thought.

This discovery might be construed as indicating that the entire exposure at the type locality should be considered Upper Harrison. The writer suggests that the occurrence of these structures in the lower portion of the formation is not abundant enough to warrant any change in the classification of the beds, but shows only that the occurrence is not as limited as was previously supposed.

HEAVY MINERAL ANALYSIS

Standard procedures were followed for petrographic identification of heavy mineral grains. A method of line counting, suggested by Doeglas (1940), which introduces controlling factors on the statistical error, was used but without the facility of a mechanical stage. A series of traverses across each slide was made, using high power (360x), thus minimizing the human element of selection introduced when counting all mineral grains in a field. Also, as Doeglas points out, the probability of larger grains entering the field or crossing the intersection of the cross hairs of the microscope is greater than the probability of smaller grains; therefore, the abundance designations are more nearly in accord with weight percentages than if all grains were counted. The abundance designations in this study are based on percentages of 200 mineral grains identified on each of the 73 studied slides. Thus, the study is based on the examination of approximately 15,000 mineral grains.

All the opaque minerals were placed in one category; however, some qualitative breakdown was made. The different opaque minerals differentiated under reflected light are: magnetite, ilmentite, pyrite, hematite, and chromite(?).

The method used to represent the relative abundances of the heavy minerals is modified after that suggested by Milner (1940). Milner's system uses the integers 1

[2] The exact position of these finds is given in the local section descriptions in the original thesis, "Petrographic analysis and stratigraphic relationships of the heavy minerals of the Harrison Formation in northwestern Nebraska," on file in the Department of Geology Library, University of Nebraska.

through 9 assigned to abundances of flood, very abundant, abundant, very common, common, and so on. These word designations lack a sharp quantitative nature and allow human judgment to affect the accuracy. A. L. Lugn (personal communication) has suggested that different percentage ranges could be shown by a 1-through-9 system representing the nearest square root of the percentage of any mineral found in the sample. Such a system will yield a simple representation of abundance illustrated in terms of integers, facilitating a quick evaluation of the relationships shown. Also, the rounding of the percentages to the nearest square root averages most of the statistical error inherent in the methods of counting and identification of mineral grains. It is thought also that this method yields a more quantitative representation of the mineral abundances than the methods designating flood, abundant, common, and so on. Table 2 shows the percentage ranges that have been assigned to each integer.

TABLE 2.—*Percentage interval assignments to integers based on square roots of heavy mineral percentages*

9	greater than 72%
8	56½% through 72%
7	42¼% through 56%
6	30¼% through 42%
5	20¼% through 30%
4	12¼% through 20%
3	6¼% through 12%
2	2¼% through 6%
1	¼% through 2%

Tabulation of Heavy Mineral Counts

Several methods of tabulating the mineral counts were tried in efforts to make more apparent any significant heavy mineral relationships. The minerals were grouped according to their mineralogical classification, placing amphiboles together, pyroxenes together, and so on. This arrangement, although convenient from point of view of classification, did not make apparent significant trends among these groups.

Another method, which it seemed might yield some significant interpretations, consisted of compiling three lists of minerals for each section, one listing the minerals which occur in greater abundance upward in the section, another listing those minerals which decrease in abundance upward in the section, and a third listing those minerals which are equally abundant throughout the sections. One or two interesting relationships were evident from this tabulation and are discussed below.

The method of tabulation used in this report (table 3) utilizes a grouping of the minerals which characteristically may be derived from a single type occurrence (for example, pegmatite, contact metamorphic). The major difficulty in this method of tabulation is introduced by the fact that several of the minerals may occur in more than one category, and no accurate division of the percentages of a given mineral can be assigned to the various categories in which it may occur. However, if this situation is kept in mind while examining the table and if the categories are not thought of as representing inflexible groups, some significant relationships may be seen.

The presence of minerals characteristic of some particular provenance indicates that such a provenance has contributed sediments to the area of deposition. Also, any changes in the abundance of an entire group or a major portion of a group may be construed as indicating a change in the relative proportion of sediments being derived from a provenance.

RESULTS AND CONCLUSIONS

In general, it is apparent that heavy minerals derived from a number of different provenances are present in the Harrison Formation. Both pegmatitic and contact metamorphic minerals have been identified as well as a number of minerals which may have had their origin from either plutonic-igneous or metamorphic terranes. This indicates a mixing of the minerals from original sources. It should be noted that some of the more stable minerals may be reworked from earlier sediments, probably of earlier Tertiary and Cretaceous ages, originally deposited to the west of the study area. As there has been considerable chemical action and abrasion affecting the mineral grains, the less stable minerals are either very rare or not present. Evidence is the absence of olivine which, according to Pettijohn (1941), is one of the least stable common heavy

TABLE 3.—*Relative heavy mineral abundances in various sections of the Harrison Formation*

Section No. and Name	Sample No.[3]	Depth in Section (feet)	Pegmatite: Rutile	Spodumene	Titanite	Topaz	Tourmaline	Monazite	Plutonic Igneous: acid basic Apatite	Zircon	Hypersthene	Enstatite	Mellilite (?)	Opaque	Igneous & Metamorphic: Anatase	Augite & Diopside	Hornblende & Glaucophane	Biotite	Muscovite	Metamorphic: (Contact) Actinolite & Tremolite	Andalusite	Anthophyllite (?)	Corundum	Dumortierite	Epidote	Garnet	Kyanite	Ottrelite	Sillimanite	Spinel	Staurolite	Vesuvianite (?)	Zoisite	Misc. Leucoxene	Shard
1. University and Carnegie Hills	9	6 – 13		1	2	1	2	3	1	1	2			6		4	3	2			1				1	1	1	2		2				2
	8c	13 – 14.5	1		2		2	4		1	3			5		3	4	2							2	2	1	2						1
	7	30.1– 32.3	1	1	2	1	1	2	1	1	2	1		4		3	3	1	1		2	1				1		1	1				1	6
	6	48.6– 52.1	1		3	1	1	4		2	3	2		4		4	4	2							1	2								1
	5	56.1– 57.1	1		1		3	3		2	3	1		3		4	4	3			2				2	1		2						3
	4	48.6– 53.6	2	1		1	2	2		2	2	1		4		5	5	3			1				2	2		1						2
	3	53.6– 63	1		2	2	2	2		1	3	1		2		4	5	3		1					2	1		2					2	2
	2	65 – 75.6	1		1	2	3	3		1	3	1		3		4	4	2			1					2	1	2		2				3
	1c	86.6– 91.6				2	1	3		3	2	2		3		4	5		2	1					2	1	1				1			3
2. South of Andrews, Sioux Co.	24c	0 – 6	1		3			1		2	3	1		4		3	6	1	1	2	1				3					1			1	1
	23	41 – 65			3		1	2		1	2	2		4		3	6	1		2	1					2	1		1				1	3
	22	65 – 93	1		2		1	2		2	3	1		5		2	5	1		2	1		1	1	3	1	1			2				1
	21c	93 – 99	1		3			2		2	2	2		4		3	5	2		2	1				3	2	1	1		1			3	
	20	99 –119			4	1	1	2		2	2	1		5		2	5	1		2	1		1		2	1	1			1				2
	19c	119 –127			3		1	2		3	3	2		5	1	3	5	1			1				3	1	1	1		1			3	1
	18	127 –150			2		1	2		3	2	2	1	4		3	5	1		1	1				2	1				2			1	2
	17c	150 –153	1		3		1	3		2	2	2	1	5		3	4	1		2			1		3	1	1			1			2	1
	16	153 –174			2	1	1	2		3	3	1		4		3	5	2		1	1				2	2	1		1	2			1	1
	15	174 –196	1		3			3		3	2	1		5		3	5	1		2					2	1	1			1			1	1
	14	196 –204			2		1	3		3	2	1		4		3	5	2		1	1				3	1				1			1	3
	13d	200			2		2	3		2	3			4		3	5	1		1	1				2	1	1			1			1	2
	12	196 –204		1	2		3	2		3	2	2	3	3		4	5	1		1					3	2	2		1	2			1	2
	11c	230 –235			1	1	2	3		3	2	3		4		3	4	2	1	1	1				1	1	2			1			2	1
	10c	268 –271		1	2		2	3	1	3	4	1		4	1	3	3	2			1				3	1	3			2	1		2	
3. Giant Bowling Ball Outcrop	31c	0 – 2	1		2			2		2	3	2		4		2	6	2		2					3	1	1			2			1	
	30c	7 – 8.5		1	2		1	2		1	3	2		5	1	3	5			2					2	1		1		2			1	
	28	8.5– 38.5	1		3	1		2		2	1	1		5		3	5	1		2					2	1	1		1	1	1		2	3
	27	41 – 65	1		2	1		2		2	2	2		4		3	6			1					2		1		1	2			2	1
	26	65 – 75	1		3			2		1	1	2		6		2	5			2	1				2	1	1			1			1	2
	25c	97 –103	1		3			2		1	2	1		4		3	6	1		1					3					2			3	2
4. Harrison type locality	56	0 – 31			2	1	2	3		3	1	2		5		4	3	1		2	1				1	2				1			1	2
	55c	31 – 34			2		2	2		3	2	2		5		2	4	1	1	1					3	1	1		1	2			3	
	54	34 – 66			1		2	2		3	2	2		5		3	5	1		1					2	1				2			2	1
	52	97 –107			2		2	2		3	1	1		4		4	5	2		2	1				2	1				1			1	2
	50	113 –118			1		2	3		3	3	2		4		3	4	2		2	1				3	1		1		3			1	1
	49c	119	1				2	2		3	2	1		5		4	4	1		2	1				2	1				1			1	2
	48	119 –137	1			1	2	2				1		5		3	5	2		2					2	1				2			1	1
	46	148 –158	1		3		2	3		2	3	1		5		3	4	2		3					2	1			1	2	1		1	2
	45	167 –187	1		2		1	3		2	3	1		4		3	4			2	1				3	1	1			2	1			
	44	191 –198			1	1	1	3		2	2	2		5		3	3	1	1	2	1				2	1				2			1	1
	43	200 –210			1	1	2	3		3	2	1		5		2	4	1		2					2	1				3			1	2
	41	218 –224	1			1	1	3		2	2			5		3	4	1		3					3	1				2			1	2
	40	241 –250	1				2	2		2	3	1	1	5		3	4	1		2	1				1	1	1			3			2	1
	39c	252 –255	1		1	1	1	2		2	4	1		4		3	4	1	1	2	1	1			2	1				2				1
	38d	270			1		2	2		2	3	2		4		4	4	1		2	1				2	1				3	2			1
	37	255 –280			2		3	2		1	3			5		1	5	1		2	1				3	1			1	3			1	1
	36	282+	1		2		2	3			4	1		5		2	3	2		1	2				3		2	1					1	
5. South of Chadron	66	0 – 9			2	1	1	2		3	2	2		4		3	5	1	2	3					2	1	1			2			1	1
	65c	9 – 11.5		1	2			2		2	3	1		4		3	6	1		2					2	1	1			1				1
	64	19.5– 24.5		1	3			2		1	3	2		5		3	5	1	1	2			1		2	1	1			1				2
	63	29.5– 33.5			2		1	1		2	1	1		4		4	6	1		2	1				3	2	1			2				1
	62c	33.5			2		1	1		1	2			5	1	3	6	1	1	2	1				2	1	1			1			1	1
	61	44 – 60			2			2		2	2			5	1	4	6	1	1	2					3	1				1	1		1	2
	60	60 – 74			1	1		2	1	2	3	1		5		3	6	2		2					2	1				2				1
	59	74 – 89		1	2			1		3	3	2		4		3	5	1		1					2	2				2			1	2
	58c	89 – 92	1	1	2	1		2		2	3	2		4		3	6	1		2					3	1				1			1	2
6. Bryann Canyon	76	19 – 32			2	1		1		2	3	2		4		3	6	1	1	1					3	1				1			1	1
	75	32 – 50	1		3	1		2		2	3	1		4		4	5	1	1	1					2	1			1				1	1
	74c	75 – 77			2	1		2		2	3	1		5		3	5	2	1	2					3	1	1	1		1				
	73	77 – 84	1		2			1		3	3	1		5		3	5	2	1	1					2	1				2			1	
	72	85 – 93.5		1	3	1		2		2	3	2		5	1	3	5	1	1	2					1	1	1			2			1	
	71c	93.5– 98	1		3			2		2	3	1		6		3	5	1		2					1	1			1	1			1	1
	70	98 –103.5			2	1		1		2	4	1		4		3	6	1	1	1					2	2				1			1	2
	69	103.5–112.5			2		1	2		2	2	2		4		3	6	2	1	1	1		2		2	1			1	3				
	68	115.5–126.5	1		3	1		1		3	3	1		3		2	6	2	1	2					3	1	1			2				1
	67c	126.5–127.5			1	1		1		2	3	2		4		3	6	2	1	1					1		2			2			1	1
7. Scotts Bluff	80c	0 – 9			2	1	1	1		2	2	1		5		3	6	1	2	1					2	1	1			1			1	
	79	28 – 50	1		3			1		3	2	1		4		3	6	1	1	2					2	1	1		1	2			1	1
	78	57 – 72			2	1		1		3	2	2		4		3	6	1		1					3	2			1	1				1
	77c	81 – 84		1	2	1		2		2	2	1		3		3	6	1		1					3	2	1		1	2				1

[3] c = concretionary layer; d = daemonelix.

minerals and a general lack of abundance of other unstable minerals of metamorphic origin such as andalusite, dumortierite, kyanite, and sillimanite.

The presence of volcanic ash shards in the heavy mineral concentrates indicates first that considerable volcanic ash must be present in the light fraction since the specific gravity of the ash is near or less than that of quartz and, secondly, that these sediments accumulated during a period of explosive vulcanism in the West. Wahlstrom (1947) discusses Miocene and Pliocene vulcanism in the Rocky Mountain National Park area and cites other such eruptions in an area in northeastern Colorado.

"In northern Colorado near the Wyoming State line and in northeastern Colorado the White River formation . . . and Arikaree and Ogallala formations . . . contain abundant pyroclastic material, chiefly ash. It is not certain whether the ash in the Ogallala formation is of original or reworked material from underlying formations. In any event, the presence of ash in the White River and Arikaree formations points to abundant explosive volcanic activity in the northern part of the Front Range during Oligocene and Miocene."

The abundance of shards in sample 7 (table 3, section 1, University and Carnegie Hills) is probably a reflection of an accumulation of volcanic ash in a pond or stream deposit.

The pegmatites of the Front Range may have contributed the pegmatite minerals reported. However, the distance of sediment transport undoubtedly accounts for the thorough mixing of these minerals with those from other sources. It is interesting to note that titanite (sphene) occurs in greater abundance in the upper portion of all sections studied except the Giant Bowling Ball outcrop (section 3) which is composed of lower Harrison sands only. Also, tourmaline increases in abundance upward in four of the sections. It is difficult to assign a great deal of significance to these trends, as they are not marked by major anomalies, and the relative abundances of the other associated minerals do not substantiate these trends.

In conclusion, no widespread heavy mineral zonations are apparent from the present data. The writer feels that this is primarily a result of the distance that these sands have been transported and the consequent mixing of sediments from many sources. The Hartville Uplift and the Laramie Range have contributed largely to the formations comprising the Arikaree group, and possibly some sands have been derived from as far distant as the Front Range in northeastern Colorado, and from the Bighorn and Wind River Mountains farther west in Wyoming.

Some differences in abundance, particularly of the metamorphic minerals, are evident in an examination of the minerals reported by Hunter in the Ogallala group (personal communication), and it may be possible to establish zonations in the Tertiary formations of Nebraska on a larger scale than has been attempted in this study.

The presence of the newly discovered Daemonelicies in the lower portion of the Harrison Formation is noteworthy. However, these new finds do not appear to be widespread or abundant as in the higher beds, having only been noted in the type locality. It is not feasible to make any change in the classification of the beds, but only to note that the phenomenon is present in greater or less abundance throughout the formation in some localities.

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FIGS. 1–5, MARCH, 1961

PATTERN OF TALCHIR SEDIMENTATION IN BURHAI GONDWANA BASIN, BIHAR, INDIA[1]

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ABSTRACT

A detailed sedimentary environmental study has been attempted in Upper Carboniferous (Talchir Series) sediments in a small basin in eastern India. The lowest sediments were laid down in front of a glacier during the extensive Upper Carboniferous glacial epoch and represent glaciofluvial outwash sediments varying laterally into glaciolacustrine sediments. Fourteen boulder conglomerate bands have been identified and interpreted as representing oscillations of the glacial front. Typical varved silts with a large number of rafted pebbles and boulders have been seen. These sediments are overlain by siltstones and silt-shales which probably represent valley train sediments, the glacier having receded. Current flow in these and lower beds was consistently from the west-southwest where the glacier existed. Chloritic arkoses found further up the column are probably stream deposits.

The question of the origin of the Gondwana basins as well as of the absence of tillite in Burhai and four nearby basins is discussed.

INTRODUCTION

The rocks of Gondwana System are important in India since they supply more than 98 percent of the coal consumed in the country. Very little attention has so far been given to sedimentation and tectonics of these rocks. A small basin in the eastern part of India (fig. 1) has been selected by the author for the purpose of detailed sedimentary environmental study in rocks of the Talchir Series, the lowest series in the Gondwana System. The Gondwana sequence is summarised below:

Lower Cretaceous	Jabalpur Series
Jurassic	Rajmahal Series
Upper Trias	Mahadeva Series
Lower Trias	Panchet Series
Permian	Damuda Series (containing coal)
U. Carboniferous	Talchir Series

The Burhai Basin (24° 23′ N: 86° 30′ E) consists entirely of Talchir rocks. It is situated 8 miles north of Jagadishpur Rail Station which is on the Eastern Railway 183 miles northwest of Calcutta.

Preliminary geologic mapping in the area on an inch to a mile scale was done by W. L. Wilson in the ninteenth century (unpublished map, Map Section, Geological Survey of India). So far, there has been no published work except a few short notes (De, 1948; Niyogi, 1958a, 1958b; and Mahapatra, Misra and Rao, 1959). The present writer first visited the area in 1947, but the detailed fieldwork for sedimentary environmental analysis was undertaken in January 1957.

Talchir rocks are found at the base of all Gondwana coalfields, which have been shown in figure 1. Rocks of the Talchir Series were first described in 1856, the year of formation of the Geological Survey of India (Blanford and Theobald, 1856, p. 40). In succeeding years a mass of information has accumulated. The most recent and most complete review is by Fox (1931, p. 218–27). Lowermost beds in the Talchir Series, the Talchir Boulder Bed, are believed to be glacial deposits formed by a continental glacier that covered most of the Deccan shield in Upper Carboniferous time. These basins are generally supposed to have originated by trough faulting that was initiated in Talchir times.

GEOLOGIC SETTING

The Burhai Basin is approximately 3 miles long and 1 mile wide. It has an east-west extension. As in other Gondwana basins in India, the Talchir rocks were deposited on the upturned edges of a highly deformed Archaean basement after a long time gap. The Talchir rocks here have been

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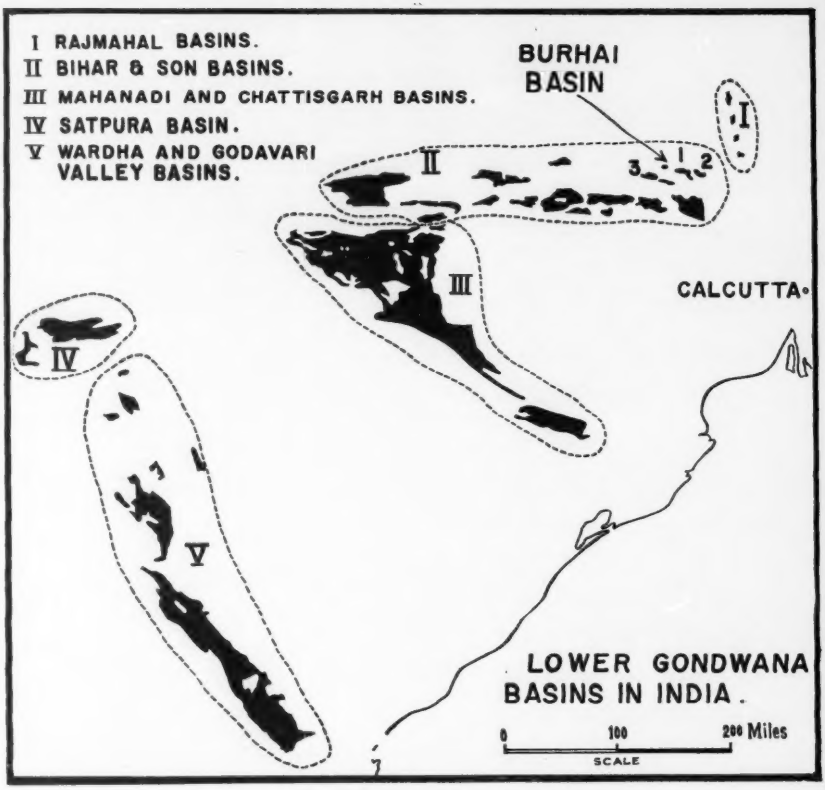

FIG. 1.—Lower Gondwana Basins in India.

divided into the subdivisions shown in table 1.

METAMORPHITES

The metamorphic rocks of the area include quartzose feldspathic gneisses, muscovite schists, quartzites, and hornblende gneisses. The whole sequence is tightly folded and has been veined intricately by granitic and pegmatitic materials. There are also some intrusive basic rocks now appearing as pyroxene and hornblende gneisses.

BOULDER CONGLOMERATE COMPLEX

In all the publications of the Geological Survey of India, the lowermost rocks of the Talchir Series have been referred to as the Talchir Boulder Bed. However, because of the varied lithology and the complicated interfingering relations between the components, the present writer has found it more convenient to assign the name of Boulder Conglomerate Complex to this group of beds. The maximum thickness of this stage in this basin is nearly 80 ft. The rocks have a gentle dip of 6° or 7° in an easterly or east-northeasterly direction.

There are three chief components in the Boulder Conglomerate Complex. In addition to the boulder conglomerate beds there are arkoses and siltstone/silt-shale alternations which are usually interbanded. There are frequent and complicated variations in both vertical and lateral directions. Thickness of

TABLE 1.—*Talchir rocks of the Burhai Basin*

Gondwana System Talchir Series	Arkoses, chloritic and greenish	100 ft
	Siltstones and silt-shales	50 ft
	Boulder Conglomerate Complex—Boulder conglomerates alternating with and varying laterally into mauve arkoses, mauve shales, laminated siltstones, and needle shales	80 ft
	Unconformity	
Archaean System Metamorphites		

individual layers may be anything between a fraction of an inch and 6 ft.

Boulder Conglomerates

Those beds which may be called boulder conglomerates in the strict sense of the term are made up of particles of assorted sizes ranging from boulders 2 to 3 ft across down to sands and silts. However, the proportion of silts is low and the rock is made up of a high percentage of boulders, cobbles, and pebbles set in a fresh arkose matrix. There is a definite tendency for both sorting and stratification in all the lower beds while the upper beds are fairly well-sorted and well-stratified. In both these respects these beds do not possess the most striking characteristics of till and tillites (Pettijohn, 1957, p. 267); here the phenoclasts are more abundant than the matrix, and neither the phenoclasts nor the matrix is structureless. Evidently these beds represent washed tills derived by glaciofluvial reworking of stony till that would be expected in this area abounding with hard and resistant rocks. A crude cross-bedding is sometimes seen in the conglomerates, individual units being 3 to 5 ft thick. Cross-bedding fans point up towards a west-southwest direction, indicating that current was flowing from that direction.

Fourteen boulder conglomerate beds which range in thickness from 10 in. to 10 ft have been noted. Almost all of the conglomerates are wedge-shaped in the sense that individual beds that are conglomeratic in the west or south-west are seen to pass on to arkoses in the down-dip direction, while near the centre of the basin silty and clayey materials have been deposited. This indicates that the main direction of flow of water was from the west-southwest. There was also subsidiary flow of water and sediments from the northern and southern edges of the basin. As a result, tongues of coarse material from north and south edges invade short distances into the fine materials in the central part of the basin. These "plaster conglomerates" as well as the pattern of down-dip variation in conglomerate bands have been diagramatically represented in figure 2. The boulders and pebbles in these plaster conglomerates are comparatively larger in size and are more angular. The composition of the boulders and pebbles is also closely related to the adjacent bed rock. All these justify the name "plaster conglomerate"

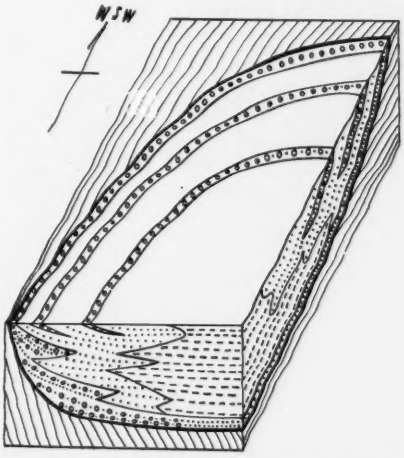

FIG. 2.—Pattern of lateral and down-dip variation in conglomerate bands. Front of the block is nearly 400 yards long.

given to these marginal conglomerates (Shrock, 1948, p. 92). These are made up of materials which have slid and crept into the basin along steep slopes. These materials have been subjected to some amount of water sorting.

Boulders are generally made up of gneissic materials, while quartzite and vein quartz boulders are also quite frequent. There are some garnetiferous amphibolite boulders which must have been transported from the southwest for a distance of at least 40 miles. As previously mentioned, the boulders in the plaster conglomerates came from the immediate neighbourhood. There are a few bands of hornblende gneiss near the southern margin of the basin which have supplied the large number of boulders and pebbles of that rock found in the southern plaster conglomerate. In some places conglomerates contain sandstone and shale pebbles which indicates concomitant erosion.

Boulders here display nearly all the characters of glacial boulders mentioned by Von Engeln (1930). Though many of the boulders are well-rounded, a large number of boulders possess the typical polygonal flat-iron shape, with well-developed concave facets and snubbed edges. Naturally, glacial characters are better developed in a larger number of boulders in the plaster conglomerates in which faint scratches and striations also are to be seen. Boulders in southwestern conglomerates, on the other hand, are seen to have undergone sufficient rolling which has modified many glacial characters. An interesting observation is the general parallelism exhibited by the largest facet on the boulders to the direction of foliation in the rock.

Arkoses

Arkoses associated with the boulder conglomerates are mauve-colored because of the presence of a large quantity of fresh and angular pinkish feldspars. They are coarse-grained sandstones and are moderately well-sorted. The arkoses are extensively cross-bedded. Here cross-bedding is of the trough-type (McKee and Weir, 1953). Cross-bedded units are generally 1 to 3 ft thick. Study of a large number of these cross-bedded fans indicates that the over-all flow was from the west-southwest. Current ripple marks are quite common. The average wave length in these is 4 in; the amplitude is approximately $\frac{1}{2}$ in. The direction of current flow fully agrees with the direction indicated by cross-bedded fans. The presence of polygonal shrinkage cracks indicates that the sediments were subjected to seasonal uncovering.

In many places these arkoses are full of very big faceted boulders, the sizes being much larger than the average boulder size in the boulder conglomerates. Presence of compaction structures below most boulders indicates that these boulders have been rafted by icebergs floating in small lakes or sometimes by blocks of river-ice floating down glacial streams during spring thaw.

Rhythmic alternations of mauve and green arkoses with siltstones are quite common. Each layer is from a fraction of an inch to a few inches in thickness.

Among other structures, intra-formational breccias with angular chunks of mauve and green shales in the matrix of sands are quite prevalent and testify to occasional increase in turbulence of the glacial streams. Many evidences of sub-aqueous sliding are present. Subaqueous sliding was perhaps caused by deposition on steep and unstable slopes and have given rise to twisted sandstone blocks. Effects of this feature are often confined to one particular layer, layers immediately above or below remaining undisturbed.

A few sandstone dykes have been noted. These are usually 2 to 3 inches in thickness and have intruded by injection into mauve siltstones. Generally these are associated with areas of disturbance in the sediments such as folding, faulting, and others. In one case a sandstone dyke has been seen to issue out of a small lens of conglomerate enclosed by siltstones. It is evident in this case that finer materials have been pressed out and have intruded the siltstones because of squeezing of this conglomeratic pocket.

Siltstones and Silt-shales

Siltstones and silt-shales are on the average thinner than the coarser components of the Boulder Conglomerate Complex. As already mentioned, near the fringe of the basin they are a minor component in the column. Near the centre of the basin they

are in dominating proportions. Shrinkage cracks are more common as well as more perfect in these rocks. Current ripple marks, too, are quite common. Here, however, they are on a finer scale and are found only in silty layers. The amplitude of the ripples is 2 to 4 mm and the wave length is 1 to 2 cm. These dimensions compare quite well with those found by Tarr (1935) in Pleistocene glacial lake silts. Rafted boulders are very frequent and are of immense sizes. Sizes exceeding 5 to 8 ft are not uncommon. Large icebergs were the agents for rafting. Very regular alternations of siltstones and silt-shales are frequently seen. Individual layers are a fraction of an inch in thickness. In many places these alternating layers are arranged in couplets; the lower silty layers, generally light green or mauve in color, grade imperceptibly up into the thinner shaly layer. The latter is invariably of a deeper color, either dull green or deep mauve. Above this, with an abrupt break, is another light-colored silty layer, the lower component of the overlying couplet. Many granitic and other pebbles and boulders with typical glacial facets and showing compaction features below are found in these rhythmic sediments. There can be little doubt that these are glacial varve sediments with rafted boulders deposited in proglacial lakes (Pettijohn, 1957, p. 273). Penecontemporaneous deformation phenomena are well-displayed in these laminated lake silts. In some cases this feature is likely to have been caused by grounding of icebergs in kettle lakes.

In addition, there are some green or black shales which have the notable character of breaking down into needle-like fragments because of the development of a series of close-spaced fractures. These needle shales are a characteristic associate of the rocks of Talchir Series wherever they occur in India.

SILTSTONES AND SILT-SHALES

Siltstones and silt-shales overlie the Boulder Conglomerate Complex conformably. General characters of these resemble those of the siltstones and silt-shales component of the Boulder Conglomerate Complex. Mud cracks and ripple marks are present. Individual beds of siltstones and silt-shales may be a few feet in thickness. The total thickness of the unit is 50 ft. In some ways, however, these beds differ from those lying below. They do not have drifted boulders; neither do they have needle shales or layered siltstones associated with them. Moreover, although there is some amount of lateral and vertical variation, nothing compared to the complicated interfingering relation found in the Boulder Conglomerate Complex is present in these rocks.

CHLORITIC ARKOSES

Chloritic Arkoses, the hill-formers in the area, are almost 100 ft thick. In common with other formations, these beds dip at low angles in an east-northeast direction. Compared to the arkoses of the Boulder Conglomerate Complex, these rocks are somewhat more fine-grained and are better sorted. These rocks are made up mainly of quartz with many grains of feldspar and some grains of hornblende and biotite cemented by chloritic materials. Feldspars are somewhat weathered. Cross-bedding is well developed. The cross-bedded units are 8 inches thick. A large number of scour-and-fill structures, which range in size from 1 in deep to as much as 5 ft deep, are present. An interesting feature is the frequent presence of scours or cuts that are oriented in opposite directions in succeeding layers (fig. 3). This has been interpretted as being caused by currents flowing in opposite directions during deposition of succeeding layers. The valley of a meandering stream is perhaps one environment in which this feature could have originated.

ENVIRONMENTAL INTERPRETATION

Possible environments of deposition have been suggested in the preceding section in connection with individual sedimentary features. The over-all environmental pattern will now be reconstructed.

The presence in the boulder conglomerates of faceted boulders and pebbles, extreme variation in grain size, the pattern of vertical and lateral variation as outlined above, and the association with laminated lake silts and varved sediments containing many rafted pebbles and boulders define the glacial origin of the Boulder Conglomerate Complex. Study of Pleistocene glacial deposits indicates that while no stratifica-
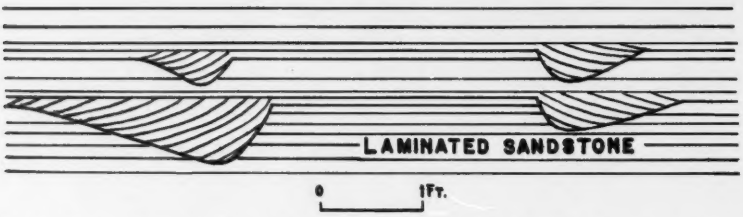
FIG. 3.—Scour and fill structures with opposite orientation in Chloritic Arkoses. (In section.)

tion is to be seen in basal tills, some stratification may be expected in super-glacial till which may have been mildly worked by melting water (Flint, 1947, p. 113). No sorting has been reported in either basal or super-glacial tills. Since all the boulder conglomerate beds are to some extent stratified as well as sorted, it is evident that none of these have been deposited directly by ice.

The pattern of interfingering seen in the field between the different components of the Boulder Conglomerate Complex suggests that the latter is a proglacial deposit; glaciofluvial outwash deposits grading laterally into glaciolacustrine deposits in ice-marginal lakes. In other words, distribution of sediments reminds one of a typical outwash plain sloping into glacial lakes. According to Thornbury (1954, p. 392), "Outwash plains are produced by the merging of a series of outwash fans or aprons." It is likely that proglacial braided streams, which gave rise to these fans, in times of turbulence scooped out troughs which were almost immediately refilled. In this way the trough or festoon type of cross-bedding was formed in these sediments in a manner that is perhaps closely paralleled by McKee's experiments on the development of cross-stratification in stream current deposits (McKee, 1952, p. 59 and pl. XIIId). The pattern of cross-bedding in these outwash sediments closely resembles that shown by Shrock (1948, p. 251, fig. 217), who writes that "this type of cross-lamination is produced by rapidly shifting currents that scour out channels and then back fill them with coarse sediments." It would thus appear that the boulder conglomerates alternating with mauve arkoses represent outwash sediments. Some amount of rolling of pebbles of outwash sediments would be expected to remove the glacial scratches. In fact, Flint (1947, p. 134) states, "the facets and striations characteristic of some . . . of the stones in the basal drift and in the till are quickly worn away, for such features are very rare in outwash." This is possibly the explanation of absence of scratches and striations. In the plaster conglomerates, however, where no large transportation has taken place, faint scratches are visible. The erratic blocks that are found in mauve arkoses are likely to have been brought in by river ice. The abrupt lateral facies changes indicate that the glacial front could not have been very far to the west of the basin. Current was flowing uniformly from the west-southwest. The presence of so many boulder conglomerates indicates oscillations of the glacier front. A look at the dip section (fig. 4) through the basin would indicate that during deposition of successive layers the glacier was probably advancing toward the east-northeast. All the 14 boulder conglomerates were probably deposited in one continuous series of easterly advance.

The mauve arkoses which were deposited side by side with the moderately ill-sorted boulder conglomerates are well sorted. Simultaneous deposition of these two contrasted sediments may be interpreted by assuming that the arkose sediments had a fairly long transportation in englacial streams which began far back behind the glacial terminus.

At the same time, coarse and fine rhythmic sediments were deposited in the ice-marginal lakes in which icebergs were floating. Here, too, there were faint bottom currents from the west-southwest which gave rise to the ripple marks. It is likely that headward portions of these lakes were kept full by the gradually advancing delta,

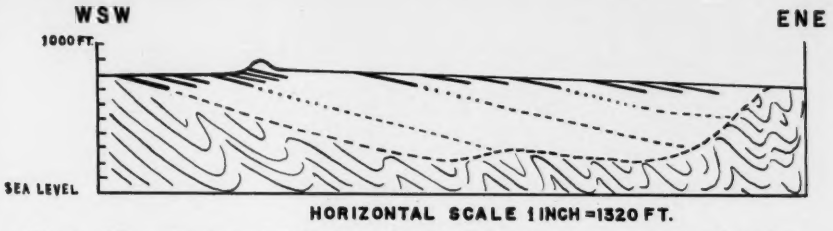

FIG. 4.—Dip section through the basin showing the fourteen boulder conglomerates (solid lines) varying down-dip into sandstone (dotted lines) and then to siltstone/shales (dashed lines).

so that portions of lake silts were subjected periodically to subaerial drying. Under such conditions shrinkage cracks were formed. Evidently these lakes were fresh water lakes, for in marine conditions varved sedimentation would not have been possible. The predominant mauve and green colors of these layered silts was probably caused by the absence of appreciable organic material (Grim, 1951, p. 231) in such a cold climate.

The environment of sedimentation of the next higher unit, siltstones and silt-shales, cannot be defined with such precision. The absence of drifted boulders as well as of needle shales and layered siltstones indicate that glacial ice, if present, must have receded far to the west. These may still be outwash sediments, diluted, of course, by river alluvium. Recession of the ice-front may be the reason for the finer grain size. The abundance of mud cracks in these beds corroborates the idea that these are stream deposits.

It seems likely that after the formation of the above beds, glacial conditions disappeared from the area altogether. The well-sorted and well-rounded nature of the medium-grained chloritic arkoses together with the presence of scour-and-fill structures with opposite orientation suggest the wide valley of a meandering stream as the site of sedimentation.

STRUCTURE

The southern margin of the basin is an undisturbed sedimentary contact while a portion of the northern boundary is faulted. The fault is of block-fault type with a small downthrow to the south. As in many other Gondwana basins, the boundaries of the basin are parallel to the local foliation of the metamorphites. Compared to other Gondwana basins, faults are rather scanty here. Another remarkable feature of the basin is the total absence of intrusives. Neither dolerites nor mica-lamprophyres, which are as a rule present in Gondwana basins, are to be seen in Burhai Basin.

OBSERVATIONS IN NEARBY BASINS

In order to compare the observations in Burhai basin with the Talchir rocks in nearby basins, the writer visited the following Gondwana basins:

1. Jayanti Basin (86°40′E; 24°10′N), 15 miles to the southeast
2. Sahajuri Basin (86°52′E; 24°8′N), 25 miles to the southeast
3. Giridih Basin (86°20′E; 24°11′N), 22 miles to the southwest
4. Taratanr Basin (86°25′E; 24°3′N), 35 miles to the southwest
5. Barakar Basin (86°12′E; 24°9′N), 32 miles to the west-southwest

The first three basins are located in figure 1 by corresponding numbers. The writer was accompanied by his colleague Mr. C. N. Rao during his visits to Giridih, Taratanr, and Barakar Basins; a preliminary summary of the observations has recently been published (Niyogi and Rao, 1959).

Similar formations in the same sequence are seen in these basins. The number of conglomerate bands is generally much less, no more than two or three being found in these basins. The first three basins contain Lower Damuda rocks together with important deposits of coal, especially the Giridih Basin. In these basins, there are a large number of faults as well as intrusives. In Taratanr and Barakar Basins, as well as in Burhai Basin,

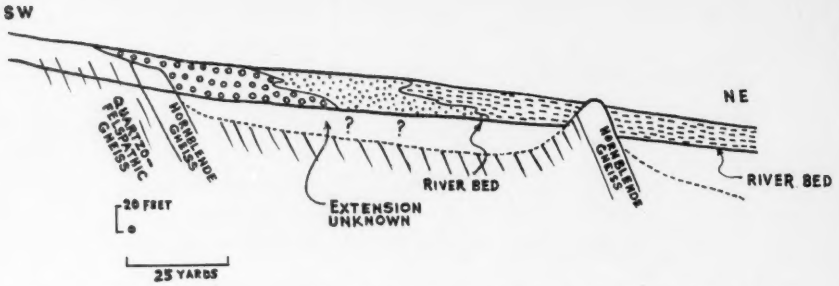

FIG. 5.—Diagrammatic representation of a river section showing the nature of the basin floor.

only Talchir rocks are present. In contrast to the other three basins, faults are fewer in these while intrusives are altogether absent.

SOME UNSOLVED PROBLEMS OF GONDWANA SEDIMENTATION

Krishnan (1958, p. 310) has stated, "A series of linear faults seem to have developed in Gondwana times." Similar opinion is expressed by Jacob (1952, p. 162): "The chief Gondwana basins of India roughly correspond with four zones of block faulting . . . these depressions served as basins for the deposition of Gondwana sediments. . . . The wide-spread block faulting was initiated towards the close of the late Carboniferous glaciation, thus including the initial Gondwana glacial sediments in most of the basins. Faulting was prominently active probably during the Upper Jurassic to Lower Cretaceous times."

Both these statements suggest that boundary faults were already existent when sedimentation started. However, one margin of the Gondwana basins generally show undisturbed sedimentary junction with underlying rocks. If faulting had preceded sedimentation, there would be fault escarpments with fanglomerates sloping from them. The "wedge arkose," built of coalescing alluvial fans that thin down away from the fault escarpment, is the characteristic sediment in a block-faulted area. The absence of wedge arkoses indicates that the marginal faults became active later on.

As already mentioned, in nearly all the Gondwana basins in India, margins are parallel to the foliation in nearby metamorphites. It would appear that the pre-existing foliation has in some indirect manner contributed in orienting the Gondwana basins. In this connection, it would be relevant to describe certain characters of pre-Talchir topography in a portion of the Burhai Basin. Near the southern boundary of the basin an excellent section is exposed on the wall of a rivulet (fig. 5). The well-foliated metamorphites dip steeply toward the north or north-northwest. The southern margin of the basin is partially delineated by a steeply-dipping band of hornblende-gneiss. Seventy-five yards to the north there is another steeply-dipping band of hornblende-gneiss which must have stood up in the basin at the time of sedimentation in the form of a series of disconnected walls arranged in a line and having gaps in between. The minimum relief of the floor exposed here is of the order of 15–20 ft within a horizontal distance of 75 yards. Soil cover is apparently lacking on this ancient surface. Effects of differential resistance to weathering seem to be well-marked. Some of the slopes appear to have been guided by the metamorphic foliation. Of course, it would be too hasty to come to a conclusion based on observations in one basin only. However, it seems to be indicated that the Talchir glacial sedimentation started in natural depressions on a surface having considerable local relief. The relief was perhaps caused by differential erosion which was controlled by the local foliation. The agent responsible for this differential erosion may have been the pre-glacial streams. The possibility that some of these natural

depressions were further deepened by the process of glacial gouging also cannot be ruled out.

A glacial environment is evidently a non-tectonic one (Pettijohn, 1957, p. 635). Along the whole front of the glacier a sheet of sediments was deposited. This suggests that in Lower Talchir times, there were connections between the separate patches of Talchirs. In Upper Talchir times or perhaps in post-Talchir times, tectonic control was established. Certain well-defined zones acquired mild to moderate degrees of tectonic activity. Block-faulting started at this stage and was intensified, as suggested by Jacob (1952) in Jurassic times. Intrusion of dolerite dykes probably had a tectonic control and took place quite late. These may be the reasons of the absence of the dykes in the three basins which contain only Talchir rocks. Paucity of faults in these three basins may also be explained in the same manner. These basins apparently did not receive any younger sediments.

In Upper Talchir or in post-Talchir times, trough faults depressed certain portions of the Talchir sediments sheet, leaving the intervening portions only to be later removed by erosion. Depressed zones now acquired the characters of unstable shelf or perhaps of intra-cratonic basin. Thus, in the isolated basins, Damuda sedimentation started in a manner which probably resembled the piedmont type of cyclothemic deposition.

Yet another unsolved problem is with respect to the till. What happened to the till? In all the six basins studied by the writer,—except perhaps in Giridih (Rao, 1957, plate IA),—the boulder conglomerates are all stratified and sorted. Absence of the unstratified drift has also been noted by Fox (1930, p. 23). The writer, along with his colleague Mr. C. N. Rao, has scrutinised published descriptions of the Talchir Boulder Bed of some 30 localities (Rao and Niyogi, 1959). Most of the boulder beds described appear to be bouldery sandstones, bouldery siltstones, or bouldery shales. All the boulders in these rocks are rafted ones. The astonishing fact is that none of the boulder beds described in the last hundred years appears to be an ice-laid deposit. All glacial deposits of Talchir age seem to have been reworked by meltwater to varying extents. The writer has no explanation to suggest except that perhaps the melting of the Upper Carboniferous glacier was so sudden that the meltwater had sufficient competence to sort and stratify all the glacial drift.

ACKNOWLEDGMENTS

The author acknowledges his grateful thanks to Professor H. R. Wanless, University of Illinois, Urbana, Ill.; it was mainly through his influence that the writer first became interested in the field of sedimentation when he was in Illinois in 1955–56. The author is also very grateful to Professor J. L. Hough for directing his attention to certain pecularities of Talchir sediments as well as for a critical reading of the manuscript. To Professor T. C. Bagchi, Head of the Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, the author is indebted for constant help and encouragement.

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FIGS. 1–4, MARCH, 1961

VARIATION IN PEBBLE COMPOSITION OF WISCONSIN OUTWASH SEDIMENTS IN THE WABASH VALLEY, INDIANA[1]

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ABSTRACT

Variation in the pebble composition of Wisconsin glacial outwash sediments in the Wabash Valley has been significantly controlled by the influx of rock fragments supplied by the local Paleozoic bedrock. Dolostone, the dominant rock type, and limestone were derived from the Silurian and Devonian formations that crop out in northern Indiana. Limestone was also furnished by the Mississippian formations that are exposed in central and south-central Indiana. Clastics were supplied by the Pennsylvanian formations that crop out in the lower Wabash Valley. Chert was contributed by one or more formations in each of the Paleozoic systems exposed in the Wabash Valley. The igneous and metamorphic rocks, whose ultimate source was the Canadian Shield, were supplied by the gravel fraction of Wisconsin till deposits. This study provides an illustrative example of the concept of progressive dilution.

INTRODUCTION

A study of Wisconsin glacial outwash sediments in the Wabash Valley was undertaken in 1958 to determine if textural and compositional properties of the sediments might be useful in differentiating and correlating alluvial terraces. As part of this study, the pebble composition within the 16–32 mm size interval of the outwash sediments was determined; the results of this determination are the subject of this paper. The objective of this paper is to describe and interpret the downstream variation in pebble composition of the outwash sediments and to demonstrate the significance of local bedrock contamination.

The area of investigation extends along the Wabash Valley from the northeastern part of Indiana to the junction with White River, a distance of approximately 280 valley miles (fig. 1).

GEOLOGIC SETTING

The Wabash River flows in a valley carved out of Paleozoic rocks. Going downstream the river flows across progressively younger strata ranging from Silurian to Pennsylvanian in age (fig. 1). It is convenient for this paper to define an upper and lower Wabash Valley. The upper Wabash Valley is that portion beginning at Williamsport and extending upstream to the source area situated about twelve miles east of the Ohio-Indiana boundary. The lower Wabash Valley extends from Williamsport downstream to the junction with the Ohio River. The two portions of the Valley are essentially dissimilar with regard to geomorphic history and lithology of the underlying bedrock. An excellent summary of the geomorphic history of the upper Wabash Valley (north of Terre Haute) has been presented by Thornbury (1958, p. 449); the physiography of the lower Wabash Valley (south of Terre Haute) has been studied in detail by Fidlar (1948).

The upper Wabash Valley is developed on bedrock consisting mainly of limestones, dolostones, and dolomitic shales of Silurian, Devonian, and Mississippian age. In the area around Williamsport, the Wabash River flows in a narrow bedrock valley cut in sandstones and siltstones of Mississippian and Pennsylvanian age. Extending downstream from Williamsport, the valley of the Wabash to its junction with the Ohio is cut through rocks of Pennsylvanian age.

Within the study area, the Wabash River crosses two major glacial boundaries (fig. 2). North of Terre Haute, the Wabash River crosses the Shelbyville moraine, which marks the southernmost advance of the early Wisconsin (Tazewell) ice sheet in Indiana and Illinois. Farther upstream, the Wabash River intersects the Champaign morainal system which represents a read-

[1] This study was submitted as part of a Ph.D. thesis, Indiana University, 1959. Manuscript received April 6, 1960.

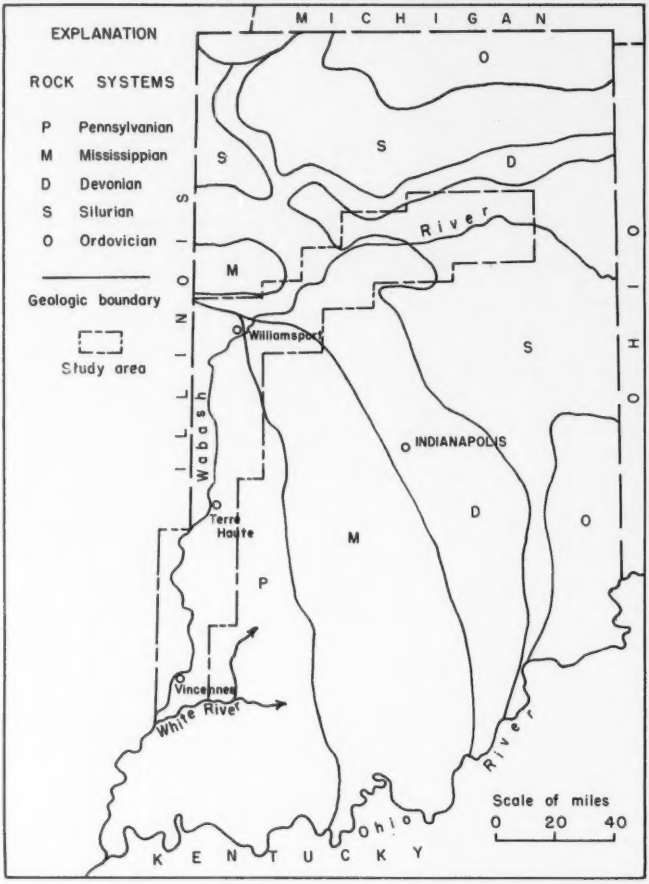

FIG. 1.—Generalized geologic map of Indiana. Adapted from Wayne (1956).

vance of later Tazewell age. The Union City and Packerton moraines, and perhaps the Maxinkuckee moraine in northeastern Indiana, mark the farthest advance of the late Wisconsin (Cary) ice sheet in Indiana. The Mississinewa, Salamonie, and Wabash moraines are stadial moraines representing minor readvances of the late Wisconsin ice sheet. Additional information concerning the glacial history of the area may be obtained from the references accompanying the recently published glacial map of the United States (Flint and others, 1959).

SAMPLING

Thirty-one samples of pebbles were collected from an upper and a lower sampling level along the Wabash Valley (fig. 3). The upper sampling level was the uppermost alluvial terrace in the Wabash Valley from which 18 samples were collected; the lower sampling level was the surface of a lower

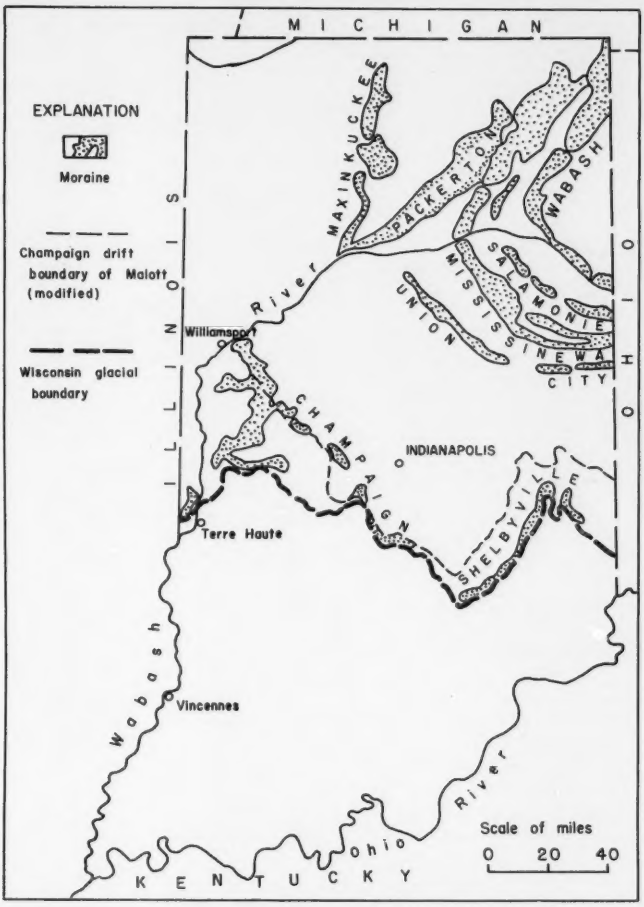

FIG. 2.—Index map of Indiana showing moraines to which reference is made in the text. Adapted from Wayne (1956).

alluvial terrace from which 13 samples were collected. The alluvial terraces from which the samples were collected have been recognized in the Wabash Valley for nearly 100 years although only in the last decade have they been mapped in detail (Fidlar, 1948; Thornbury, 1953; Thornbury and Deane, 1955; Thornbury and Wayne, 1951; Wier and Friedman, 1955). Thornbury (1958, p. 463) has summarized the existing hypotheses regarding the origin and development of the alluvial terraces.

Each sample of pebbles represented a sieved fraction of a compound channel sample taken from the face of an exposure in a sand and gravel pit. From each such sample of pebbles, a subsample of approximately constant volume was selected. Assuming that the bulk density of the pebbles is constant, the subsamples of constant volume

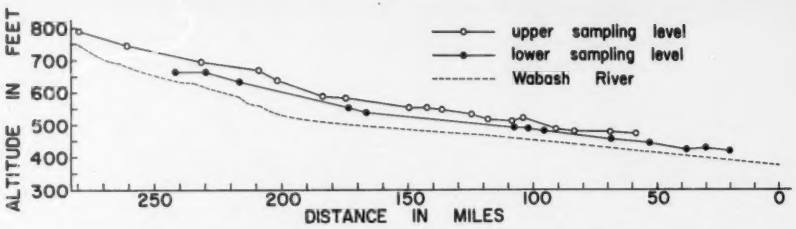

FIG. 3.—Longitudinal profiles of the sampling levels along the Wabash Valley. Distance in miles is measured from the junction with White River. Vertical exaggeration ×660.

correspond to subsamples of constant weight. It was found that 90 percent of the subsamples were within 10 percent of the average subsample weight of 2.9 kg. The median number of pebbles per subsample was 171.

CLASSIFICATION OF ROCK TYPES

Sedimentary, igneous, and metamorphic rocks were represented in every subsample. With such a diverse population of rock types, a number of classification schemes was possible. The one which was adopted might be considered by some too generalized, but since the purpose of the classification was to differentiate rock types quantitatively, a small number of categories for the sample size taken seemed necessary.

The sedimentary rocks were classified as limestone, dolostone, chert, and clastics (sandstone, siltstone, and shale). The igneous and metamorphic rocks were put together as one group with the exception of quartzite, which was considered a separate rock type. Although graywacke was identified separately, it was included with the igneous and metamorphic component because of its similarity of provenance. The igneous and metamorphic rocks, quartzite, graywacke, and a small fraction of the clastics came from the Canadian Shield, whereas the remaining sedimentary rocks had their origins south of the Shield area.

Dolostone was distinguished from limestone on the basis of texture, color, and reaction with dilute hydrochloric acid. The dolostone in the subsamples was characterized by a saccharoidal texture, light gray to white color, and a slow effervescence with dilute hydrochloric acid whereas the limestone was generally more coarsely crystalline, bluish gray in color, and reacted vigorously with acid. Comparison of these criteria with the identification of calcite and dolomite from powder X-ray diffraction patterns for selected samples verified the reliability of the method.

Argillaceous limestone and weathered dolostone pebbles are easily confused with calcareous and dolomitic siltstones on a megascopic examination. Fortunately, such borderline cases occurred in small proportions.

METHOD OF PRESENTING DATA

Two methods are available for depicting lithologic variation in a downstream direction. This may be done either as a direct plot of relative proportions of rock types or as a ratio with respect to a particular rock type. Each method has its advantages and disadvantages. In the present study the sediment dispersal pattern is complicated by moraines intersecting the Wabash Valley and the confluence of major tributary streams with the Wabash River. Also, a considerable portion of the upper Wabash Valley is a bedrock valley. Thus we have added the problem of sediment contamination to the effects of selective abrasion and sorting of fluvial sediments. The possible mutual interactions of these three processes render extremely hazardous the selection of a rock type suitable for ratio comparison with the other constituents. Consequently, variation in pebble composition in a downstream direction is depicted by plotting the relative proportions of each rock type in the size interval studied (fig. 4). The percent by weight of the different rock types for each

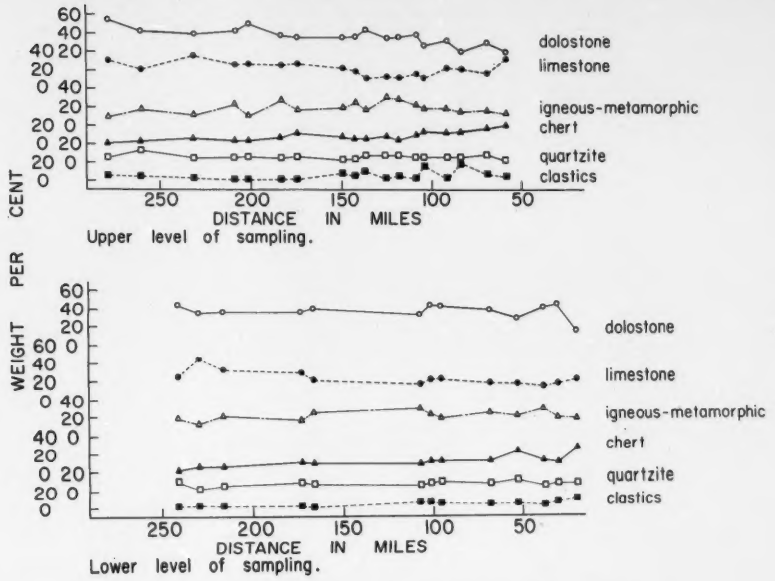

FIG. 4.—Variation in pebble composition (16–32 mm) expressed as weight percent in a downstream direction.

subsample is tabulated in table 1. The effect of selective abrasion and selective sorting upon the pebble composition of the outwash sediments is unknown, and no attempt has been made in the present study to analyze the importance of these factors.

DOWNSTREAM VARIATION IN PEBBLE COMPOSITION

The downstream trends for each rock type are depicted in figure 4.

Dolostone.—Dolostone, the dominant rock type, decreases in relative abundance downstream. Its greater relative abundance in northeast Indiana is attributed in part to the Huntington Dolomite, a Silurian formation in which the Wabash River has carved a bedrock valley.

Limestone.—Limestone pebbles decrease in relative abundance downstream for a distance, beyond which their relative abundance increases. Upon examination of the limestone types, characteristic bioclastic Mississippian limestone pebbles not found further up-stream were recognized. Such evidence indicates an influx of Mississippian rock fragments. The contribution of Silurian limestones is evidenced by the anomalous limestone high at the 230 mile point. A concomitant increase in limestone and chert relative to all of the other rock types indicates contamination because of the influx of cherty limestone pebbles derived from the Liston Creek Formation which crops out along the Wabash River and its tributaries.

Igneous and metamorphic rocks.—The igneous and metamorphic rock pebbles increase in relative abundance downstream, reaching a maximum at approximately the 130 mile point, then decreasing on downstream, although the lower sampling level does not display this trend as conspicuously as does the upper sampling level. The maximum, located 45 miles upstream from Terre Haute, occurs in an area of moraines considered to be early Wisconsin (Tazewell) in age. This suggests that the Shelbyville

TABLE 1.—*Pebble composition of the samples in the 16–32 mm size interval expressed as weight percent*

Sample number	Lime-stone	Dolo-stone	Chert	Clastics	Quartzite	Igneous metamorphic	Gray-wacke
U- 58	33.9	22.5	19.8	6.4	4.4	9.7	3.1
69	18.7	31.0	16.2	7.6	9.5	13.4	3.6
84	24.3	22.1	12.6	20.0	6.2	14.5	0.3
92	24.1	34.3	11.4	4.3	5.5	18.2	2.2
104	14.1	27.8	14.3	16.4	7.4	13.3	6.7
109	17.4	40.4	8.5	4.9	5.9	20.8	2.1
118	13.4	38.2	4.4	5.9	9.3	26.6	2.2
125	13.6	36.0	7.6	2.9	8.5	22.4	9.0
137	12.3	46.5	5.4	10.4	7.6	16.2	1.6
142	20.0	37.0	5.8	6.9	5.1	18.3	6.9
150	23.6	36.9	5.6	7.8	4.5	18.3	1.0
175	27.9	36.8	9.9	1.2	7.1	15.4	1.7
184	24.9	37.6	6.1	1.5	4.2	22.3	3.4
202	27.3	51.4	3.4	0.9	7.3	8.7	1.0
209	26.3	41.6	2.3	2.5	4.7	19.8	2.8
231	35.3	38.9	5.6	2.4	5.3	9.4	3.1
261	21.4	41.6	3.2	4.5	13.0	13.7	2.6
279	29.5	54.2	0.3	5.0	3.5	6.9	0.6
L- 20	20.7	14.4	24.1	11.6	9.8	15.7	3.7
30	16.5	43.3	7.0	6.2	8.8	11.2	7.0
38	13.2	39.5	8.6	4.1	6.1	21.5	7.0
53	17.0	28.1	19.7	4.8	10.6	17.2	2.6
68	17.3	36.7	7.8	5.7	8.7	20.8	3.0
96	21.8	32.4	10.1	6.3	11.2	15.4	2.8
102	20.9	32.3	8.3	9.6	9.6	15.4	6.2
108	16.2	32.4	6.8	8.1	6.5	26.7	3.3
167	22.5	39.9	5.5	0.5	7.2	18.4	5.6
174	28.8	34.9	8.7	2.3	8.8	11.5	5.0
216	32.3	36.0	4.4	1.1	5.5	16.4	4.3
230	43.7	34.3	3.9	2.8	2.8	8.2	4.3
241	23.9	44.5	1.2	1.4	11.2	15.5	2.3

moraine and its associated ground moraine provided a source of supply for igneous and metamorphic rock pebbles.

Chert.—Chert pebbles consistently increase in relative abundance downstream, and although the exact provenance of the chert could not be determined, it is reasonable to assume that chert was continuously supplied by the Paleozoic formations along the Wabash Valley. Wanless (personal communication, 1959) has suggested that another possible source of supply might be the chert pebbles derived from Tertiary erosion surfaces whose runoff drained into the Wabash Valley. Assuming that the processes of selective abrasion and sorting acted similarly on chert and quartzite, increase of chert relative to quartzite in a downstream direction is further evidence that chert was being continuously supplied from local bedrock.

Quartzite.—The relative abundance of quartzite pebbles remains essentially constant all the way downstream. It should be noted, however, that the fluctations in relative abundance of components present in small amounts are of lesser magnitudes than for components present in large amounts, although the percentage changes may be of equal magnitude. The rapid increase and subsequent rapid decrease in relative abundance of quartzite pebbles observed in samples U-279, U-261, and U-231 is interpreted as a result of addition of quartzite. A corresponding trend in the igneous-metamorphic rock component in the above-mentioned samples suggests that the Salamonie moraine may have contributed these components (fig. 2).

Clastics.—Clastics increase in relative abundance downstream. This increase is attributed to the continuous addition of

sandstone and siltstone pebbles derived from local bedrock of Mississippian and Pennsylvanian age. A glance at the geologic map (fig. 1) shows that a considerable portion of the Wabash Valley is developed in Mississippian and Pennsylvanian formations.

CONCLUSIONS

On the basis of the observed downstream variations in pebble composition, it is concluded that the influx of rock fragments supplied by local Paleozoic bedrock has significantly controlled the pebble composition of the outwash sediments in the Wabash Valley. It is not implied that the processes of selective abrasion and sorting are neglible here, but for the size interval studied, local bedrock contamination seems to have been a critical control factor which regulated the relative abundance of rock types.

The results of this study provide an illustrative example of the concept of progressive dilution (Pettijohn, 1957, p. 565) and also an affirmation of the statement made by Cayeux (1929) to the effect that stream pebbles reflect to a large degree the local bedrock.

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FIGS. 1–2, MARCH, 1961

MINERAL AND CHEMICAL ALLUVIATION IN A UNIQUE PEDOLOGIC EXAMPLE[1]

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ABSTRACT

Flood water from the Snoqualmie River and Cherry Creek, laden with fine silt, colloidal clay, and dissolved ions, stands quietly part of each winter season over land underlain by an old peat bog near Duvall, Washington. This water, instead of leaching and abstracting inorganic plant nutrients as is the usual role of surface water and soil, donates to the soil dissolved ions, colloidal material, and fine-grained, partially decomposed rock fragments (naturally pulverized agstone). Analyses are presented which indicate the annual contribution of the alluviation.

In the chemical weathering of rocks to soil the sequence of energy effects begins first with the disruption of relatively strong crystal bonds between ions, thereby making the ions vulnerable to pick up by plants by way of the exchange bonding energy of rootlets. As weathering advances, however, and abstraction of ions from the rocks by leaching continues, the concentration (activities) of available nutrient ions in the soil decreases, and their energies of exchange from soil clay rises above the energy of the rootlets to pull them away. Thus, weathering at this later stage is destructive to soil. Agriculture, therefore, operates most efficiently on soil in which the rocks are in a stage of partial or intermediate decomposition.

Economic geologists interested in the sources, use, and production of agstone may apply in practice the principles which may be deduced from this example in nature.

INTRODUCTION

The geologic effect of meteoric water on soil in a humid climate tends typically to be destructive to the soil in its role as a source of nutrient ions for plants. For example, the mechanical effect of running water is to remove from the topsoil its more mobile finer fractions and light-density organic matter, to eluviate colloidal matter (commonly nutrient-bearing) to lower soil horizons, and to erode the entire soil profile. The chemical, or dissolution, effect of the water is likewise usually to leach and abstract from the soil major potentially nutritive (to plants) cations, such as K, Ca, Mg; anions, such as P, N, S; and micronutrients, such as B, Cu, Mo, Zn.

The reverse (or constructive) effect, that is, addition of solids and ions which provide nutrients in substantial amounts to plants is less common in occurrence than the destructive effect, and an example of it is the subject of this report. Also, the alluviation to be illustrated differs from geologically typical alluviation that unfortunately leaves upon the soil, in addition to beneficial substances, relatively large amounts of deleterious material, such as sand or gravel that is excessively coarse in texture, or materials that are low in, or devoid of nutrients—for example, quartz, stripped clays, or lateritic material.

Chemical weathering (a common accompaniment of alluviation) assumes also antithetical roles in the supply of plant nutrients. At early to intermediate stages of rock decomposition chemical weathering releases and mobilizes the nutrient ions in a rock at a relatively low level of exchange bonding energy in terms of root exchange energy, whereas in the stage of late, intensive weathering, it decreases the concentration of nutrient ions, thereby raising the binding energy of them to the soil above the exchange energy of the roots.

Locality Studied

The locality under consideration occurs on the river flood plains near the confluence of Cherry Creek and Snoqualmie River approximately 2 miles northeast of Duvall, Washington (see Monroe, Washington Quadrangle topographic map). The specific tract from which samples of flood water and silt and soil were collected for analysis bears the name, "Hunza Farm" which occupies approximately 400 acres in sec. 7, T.26N,

[1] Manuscript received February 26, 1960.

R.7E., King County, Washington. Hunza Farm was chosen for sampling because (1) it fulfills the geologic conditions for the unusual type of alluviation, and (2) the flood waters presumably replenish each winter a considerable part of the nutrients removed from the soil by the crop shipped annually off the land. Corollary interest attaches to Hunza Farm because its name is adopted from that of the state of Hunza, in Pakistan, where reported irrigation by nutrient-rich glacial milk has been suggested as an initial and essential phase in a sequence of nutrition that is said to culminate in amazing virility and longevity of its residents. The farm (in Washington), which produces canary grass (neither endorsed nor condemned by this report) that is marketed for its content of organically combined mineral substances and vitamins, is owned and operated by Messrs. F. F. Hampson and George Hall, who kindly supplied information about the farm when the region was visited in July, 1959, and also collected in November, 1959, the sample of turbid flood water for our study.

According to Mr. Hampson, the farm (and vicinity) is inundated ordinarily to a depth of 2½ ft, but during abnormal floods, such as in the fall of 1959, the water may rise to 15 ft in depth. Ordinarily little to no sand-size material is carried in by the slowly moving flood water which remains long enough each winter that most of the colloidal clay and fine silt settle to the surface of the land beneath. Simultaneously, dissolved ions in the flood water are available for ion exchange with the clay and organic matter in the soil during the several months of inundation. It is significant that most of this site is underlain by peat (an old peat bog); therefore, organic matter is abundant. Soil organic matter typically possesses high cation exchange capacity and low binding energy; thus the organic materials in this flood plain deposit are a potentially large receptor, storage, and exchange body for dissolved cations common in rocks—such as Ca, K, Mg, and Na, and the H in humic acid—and derived from the roots of plants (Keller, 1957, p. 31) during metabolism. Hence, it is expected that annual "chemical" (dissolved ions) alluviation is important here as well as alluviation of solids.

WATER, SILT AND CLAY, AND SOIL

A sample of the turbid flood water (1959) was collected in a clean, 1-gallon polyethylene bottle by Mr. Hall, mailed to the writer, and immediately processed.

Water

Dissolved materials, expressed as parts per million by weight, in the clear water were found by Pickett[2] to be as follows.

Ca 5.02	K 2.78	Si 3.01
Mg 1.34	Na 2.16	Al .017

pH 7.07 (suspension as received).

Silt and Clay

The weight of the dried, suspended matter in the gallon of flood water (1959) was .7688 gm, which is approximately 200 ppm by weight or about 540 pounds per one acre foot of water. A 2.5-ft deep, single inundation will bring in, at this rate, approximately 1350 pounds of silt per acre, and a 15-ft flood, approximately 4 tons per acre.

[2] Professor E. E. Pickett, Professor of Agricultural Chemistry, Spectroscopist in charge of Spectrographic Laboratory, University of Missouri, determined, "dissolved silica by the colorimetric molybdenum blue method of Shapiro and Brannock (1952). Dissolved aluminum was determined by a fluorimetric method in which the fluorescent intensity of the aluminum complex of 8-quinolinal (oxine) extracted from the specimen solution at pH 8 with chloroform is measured in the blue-green with a conventional fluorimeter. Interference from the other substances in the sample is negligible at the levels found.

"Potassium and sodium were determined by flame photometry using the Beckman Model B. instrument with the oxygen-acetylene atomizer burner. No corrections for interferences on these elements were needed.

"Calcium and magnesium were determined spectrographically in the water sample using spark-in-flame excitation on a 2.4 m Wadsworth grating spectrograph. The aqueous sample is atomized by a Beckman hydrogen-oxygen atomizer burner and excited by a high voltage a.c. spark (at 7 radio frequency amperes) which is arranged horizontally 1.4 cm above the tip of the burner. Exposures are made for 1.5 minutes, focusing the source on the slit, and with a 10 per cent rotating step sector covering one-half of the slit. Ten ppm strontium (as strontium chloride) is added as internal standard. The lines, Mg 2795.5 Å, Ca 3933.7 Å, and Sr 4077.7 Å, are photometered and compared with those of standard solutions.

"Sensitivities of these methods are great enough that all determinations may be made on 25 ml to 100 ml total sample of water."

Under the microscope the solid material is seen to be mostly in fine and medium silt size and fine silt-laden clay floccules. Perhaps 20 to 25 percent of the solid material is clay size and likewise clay minerals, an estimate supported by the X-ray diffractogram. In addition to many tiny particles observable (mainly by their refraction rings) when embedded in 1.540 index oil, other larger particles of the order of 40 μ in diameter and elongate particles 80 μ long are common. Optical identification of the larger particles, also supported by X-ray diffraction patterns of the bulk powder, finds feldspar, quartz, light and dark mica, minor opal and low-index material, an occasional fragment of diatoms, needle-like particles of hornblende (?) and other high-index colored minerals which are probably apatite, tourmaline (?), and titanium oxide minerals, and probably a considerable amount of a slightly colored volcanic glass having an index of refraction above 1.540.

Clay minerals identified from the X-ray diffractogram are chlorite or a chloritic mineral shown by a small, broad-based 00*l* peak at about a 14 Å interplanar spacing and illite-muscovite shown by a broad-based but sharply peaked reflection at about a 10 Å spacing. A small part of the clay expands when solvated with ethylene glycol. A reflection at 7 Å, slightly larger than that at 14 Å, is interpreted as arising from chlorite, although it is possible that some kaolinite (likewise characterized by a 7 Å interplanar spacing) may also be present. More refined clay mineral identification requiring size separation, heating, or treating of the sample with acid was precluded by the necessity of conserving all of the small amount of available sediment for chemical analysis.

The chemical composition of the bulk sample is shown in table 1.

The analysis of the sediment is not typical of any common single rock type and thus accords with the assemblage of minerals identified in the silt and clay. The amounts of silica and alumina and the appreciable quantity of each of the common metals are suggestive of a rock in the basaltic clan, but the loss on ignition is far higher than that of basalt or any common igneous rock. High ignition loss can arise from clay minerals and micas, but 8.56 percent loss is greater than can be attributed to 25 percent clay (the amount estimated to be present). Two other probable, and logically acceptable, sources of high ignition loss are organic matter and partially hydrated particles of volcanic glass.

TABLE 1.—*Chemical analyses of sediment in flood water from Hunza Farm*

	Weight percent	Mol. fraction	
SiO_2	51.09	Si	.851
Al_2O_3	15.04	Al	.285
TiO_2	0.93	Ti	.011
Fe_2O_3	4.26	Fe'''	.053
FeO	4.89	Fe''	.068
CaO	4.17	Ca	.074
MgO	3.61	Mg	.090
K_2O	1.24	K	.027
Na_2O	1.53	Na	.049
P_2O_5	0.36	P	.005
SO_3	2.85	S	.089
H_2O @ 105° C	1.41		
Loss Ig.	8.56		
	99.94		

Analysis by Bruce Williams Laboratories, Joplin, Missouri. Expense of analysis defrayed by University of Missouri Research Council Grant.

The analysis acceptably represents a mixture of fine-grained material derived from diverse rock types present in the source area drained by the Snoqualmie River, as described by Marshall T. Huntting (personal communication, 1959). "The Snoqualmie River drains an area of complex geology, including rocks ranging in age from Paleozoic metamorphics through Eocene andesites and tuffs, Miocene continental sandstones and shales, and a complex aggregation of continental glacial deposits. Included also are some large areas of Tertiary intrusive rocks, mostly granodiorite." Such an "homogenized" mixture of fine silt particles is a favorable mineral amendment to replenish an actively cropped soil.

Soil

A soil sample taken from one of the fields producing canary grass is a dark gray, silt loam that is quite rich in organic matter (more than 6 percent found in a regular soil test[3]). The test (Graham, 1959) also showed

[3] Soil was tested through courtesy of the Soils Dept., College of Agriculture, University of Missouri.

TABLE 2.—*Nutrient ions, expressed in pounds per acre per year, removed by cropping, and brought in by flood water*

	Ca	Mg	K	Na	P
Removed in crop	15.2	78.4	32	5	16.8
Suspended solids (15-ft flood)	241	175	83	94	13
Suspended solids (2.5-ft flood)	40	29	14	15	2.2
Dissolved load (2.5-ft flood)	34.1	9	19	15	n.d.

available, per acre, 84 lbs of P_2O_5; 15 lbs of K; 90 lbs of Mg; 500 lbs of Ca; and pH 4.65, and 10 milliequivalents of H per 100 gm of soil. These amounts of available ions are low in comparison with those in most mid-west "mineral" (containing small amounts of organic matter) soils, but in soils very rich in organic matter, as in this one from Hunza Fram where the ions are loosely held in exchange complexes, high nutrient productivity is possible despite low amounts indicated on a soil test. A large reserve of nutrients is not necessary if the supply is replenished annually. Canary grass is not a relatively heavy nutrient feeder or a nutrient-rich forage crop by itself.

Nutrient Budget

A limiting nutrient budget, that is, a balance sheet between nutrient elements lost from the land by crops removed and a maximum amount of those possibly added by alluviation may be drawn up for the flooded fields of Hunza farm. Although the yield of canary grass varies from year to year with the kinds of weather and other agricultural factors, an average of approximately 2 tons of dehydrated grass are removed annually from each acre (personal communication, Floyd Hampson, 1960). Marketing this crop means the removal from each acre of land per year of 15.2 lbs of Ca, 78.4 lbs of Mg, 32 lbs of K, 5 lbs of Na, and 16.8 lbs of P (computed from analysis No. 7114 of Joseph M. Cripps, Consulting Chemist, Berkeley, Calif.) Under conditions of typical extractive farming this annual debit of nutrients would result in progressive depletion of soil fertility, except as it was replenished by the artificial application of fertilizers and by natural weathering of subsoil and rock beneath. At Hunza farm, however, part or all of this nutrient depletion is replenished by the natural deposition of silt and clay from floods and by sorption of dissolved ions present in the soluble load of the flood water. The extent to which dissolved ions are sorbed by soil colloids will depend upon relative concentrations of the ions in solution and on exchange sites in the clay because the ion concentrations tend to equilibrate between these two phases.

In table 2 are shown the amounts, in pounds, of nutrient elements computed to be removed by average cropping per acre per year, the amounts of corresponding nutrient elements in silt and clay suspended in the flood water and the amounts dissolved in the water. These amounts are computed for both the 15-ft flood of 1959 and for 2.5-ft floods that ordinarily occur. The amount of silt and clay that actually settles onto the soil and replenishes it in part is not known exactly because the extent to which the silt and clay settle out varies from flood to flood. However, maximal limits can be set in terms of the flood water sample which was collected from the 1959 flood.

Likewise, the dissolved nutrient ion content is shown in table 2, but certainly not all of this dissolved load will be sorbed by ion-exchanging material. This is unfortunate agriculturally, because these ions, being in solution, are therefore available (without further rock weathering) for assimilation by plants.

Reference to table 2 reveals that the annual debit of Ca will be replenished, or more than replenished, by alluviation from flood water. The amount of Mg removed by cropping is relatively high, and although the single, 15-ft flood of 1959 carried twice the annual Mg debit, a minimum of three 2.5-ft floods are required to replenish the annual Mg removed by crops. The 1959 flood carried more K than was cropped that year, but the equivalent of two 2.5-ft floods are necessary to replenish the K removed

each year. Na is more than adequately carried by flood waters. Although both Ca and Na are more abundantly present in total composition of flood-carried, silicate solids than needed, they do not deluge the soil with Ca and Na ions because the ions are freed slowly by weathering and may be leached by the fairly heavy rainfall in western Washington. Phosphorus is being depleted faster than replenished, unless 20 ft or more of flood water each year leaves a load like that carried by the 1959 flood.

Table 2 indicates the amount of nutrient ions carried by flood water but is not specific on the amount settled out, and it refers to ions in combination with silicate but not immediately available in solution to plants. However, because of the fineness of grain size of the silt and clay, a relatively large proportion of the ions are available to plant rootlets, and it is certainly not desirable agriculturally that all of them should be highly soluble and completely available because such a condition would create an ionic imbalance in concentrations far beyond the tolerance of plants. As it is, because of the fineness of grain size and large specific surface of the particles, a fairly large proportion of the nutrient ions are available to plant rootlets, and as plant roots lengthen downward they transect the deposits of many preceding floods, each of which is a repository of nutrient ions.

Table 2 obviously does not contain enough information to be a truly precise or highly quantitative balance sheet of plant nutrients in the flood plains of Hunza farm, but it is sufficiently informative to clearly demonstrate the difference between what occurs here and what exists on farms where nothing is added to the soil except the increment from slight annual weathering of solid rock beneath the soil zones.

TRANSFER OF IONS TO PLANTS FROM ROCKS AND MINERALS

The alluviation at Hunza Farm may be further examined in terms of ion transfer from the rock particles in the alluvium to plants—which may serve eventually in the important role as food for man. The same principle applies to soils and its parent rock particles elsewhere. Such process of ion transfer may be classified from several viewpoints, namely: as rock weathering by geologists, as plant nutrition by plant physiologists, and as ion exchange within the complex body of the soil by pedologists. Still another viewpoint is from the energy barriers which modify the rate and intensity of the transfer.

Begin consideration with a fresh, primary silicate such as K-feldspar in granite. The K in the silicate is a potential nutrient ion for plants, but while it is locked within the feldspar it is relatively unavailable to plants (except to lichen, a symbiotic pair). Why is it unavailable? Because the binding energy between ions in the crystal (lattice energy) is much stronger than the exchange bonding energy of the roots of most plants (except lichen), the roots can not "pull" the K away from the feldspar. This relationship is shown diagrammatically in figures 1 and 2.

For the purpose of illustrating the energy relationship of a metabolizing root that exchanges cations with a mineral substrate, the mean value of 3500 cal per chemical equivalent observed by Woodruff (1955 a, b) for replacement of Ca by K in actual agricultural practice is used. Although the exchange energy of K for H, which will be referred to in this illustration, may be somewhat different from Woodruff's values for K-Ca, the principle of the illustration is still good. In figure 1 the growing rootlet is unable to exchange in significant amount H ion in its root atmosphere for K in the feldspar. This is shown diagrammatically also in figure 2 where the lattice energy of the fresh silicates is indicated as being much higher than the mean exchange energy of plant roots. Ions of K exposed on the surface of feldspar may be held more loosely than those in the interior, and therefore pulverizing of the feldspar, which increases its surface area and amount of exposed K, makes more K available. Obviously the mechanical energy expended to crush the feldspar breaks the strong bonds between its constituent ions. Similarly, the chemical energy active during chemical weathering of the feldspar breaks bonds between its ions, and K, being held less tightly in the partly decomposed material, is more readily available to be picked up by plant roots (by ion exchange). This condition of relatively loose binding of ions by partially decomposed minerals is shown in the stippled part, "Plant Nutrition," at the center of the

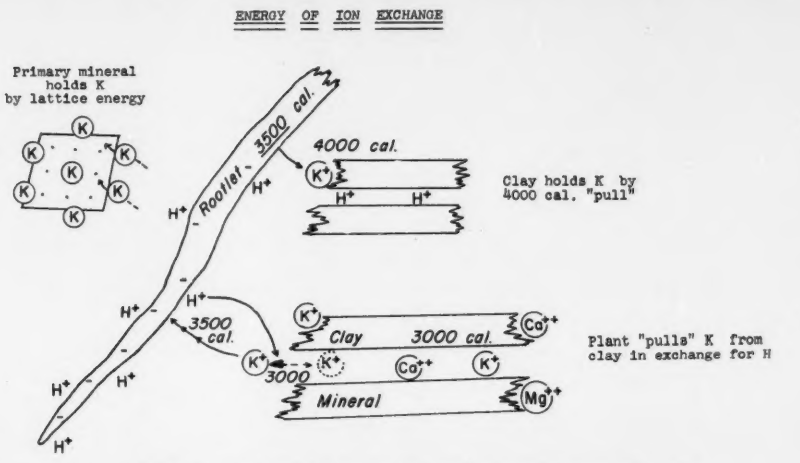
ENERGY OF ION EXCHANGE
Primary mineral holds K by lattice energy
Rootlet
3500 cal.
4000 cal.
Clay holds K by 4000 cal. "pull"
3500 cal.
Clay
3000 cal.
Plant "pulls" K from clay in exchange for H
3000
Mineral
Plant Nutrition Depends Physically Upon Competitive Intensities Of Exchange "Pull" Between Plant Roots And Clay Or Humus For Nutrient Ions
Rootlet Can Pull Nutrient Ion From Clay Or Humus Having A High Concentration Of Cation Population(thus low holding intensity) On It

FIG. 1.—Diagrammatic exchange energy relationships between a rootlet and a potassium-bearing, primary silicate mineral; a clay mineral well stocked with exchangeable metal cations; and a clay mineral scantily stocked with metal cations. The exchange bonding energy of K for H in the rootlet exceeds that in only the well-stocked clay mineral which, thus, is the only one of the three minerals from which nutrient ions can be taken.

diagram in figure 2. In this condition the partly weathered rock is a petrologic "no man's material" because it is neither well characterized mineralogically, such as that which a petrologist finds easiest to study, nor is it a well characterized clay mineral likely to interest a mineralogist studying well characterized clays and sediments. It stands intermediate and transitory between fresh rock and minerals, in which nutrient ions are most abundant although unavailable to plants, and intensely weathered materials from which most of the nutrient ions have been leached.

The flood-borne silt and clay from Hunza Farm corresponds to the left hand edge of the stippled area of figure 2. Additional hydrolysis of the sediment will release more ions from it. In terms of wide regional development of soil in response to climate, as is found across the United States, the stippled zone illustrates the extent of rock weathering where the ratio between precipitation and evaporation is 1:1 (or less than the 100-ratio isopleth of precipitation-evaporation in the United States, Keller, 1957, p. 89).

Rock weathering which has advanced thus far has been constructive toward evolving a fertile mineral soil. As weathering continues beyond this stage and leaching by rain water becomes more intense, metal cations on the aluminum silicates are replaced by H or may be leached away entirely, usually with silica, and hydrogen-rich kaolins or even bauxite or laterite may be formed. During this process the concentration (activity) of metal cations held on the weathered clay residue of the soil decreases; not only are fewer of those cations present but the exchange bonding energy of them rises. Such a condition (which prevails where much of the soil has been cropped over a long time, or "agriculturally mined," without the replenishment of nutrient substances and becomes relatively infertile is illustrated in the right-hand part of figure 2.

Agriculturists replenish soil nutrients by adding the following types of materials: organic manures such as turned-under plants and animal tissue, refuse, and excreta; relatively soluble, processed rock-derived products such as super-phosphate

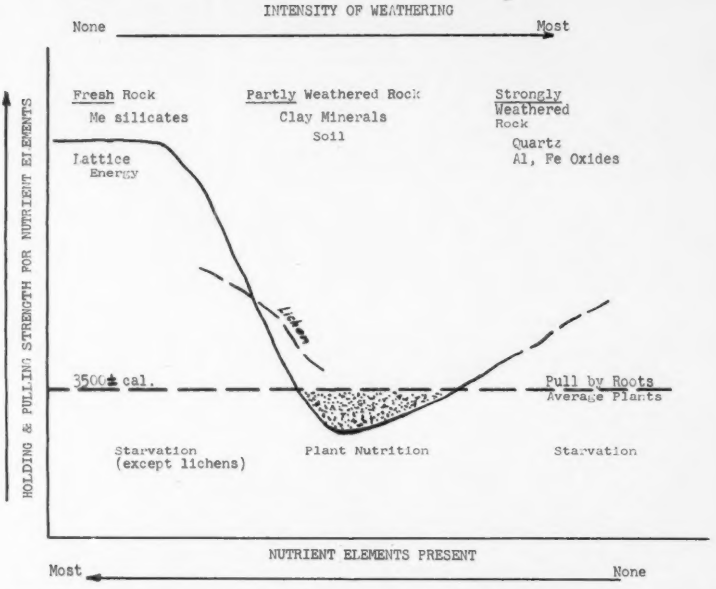

FIG. 2.—Diagrammatic representation of the nutrient, metal;(Me) cations present on rocks and minerals, their holding (bonding) strengths as affected by the degree of their weathering, and a representative level of exchange bonding energy of plant rootlets.

compounds, potash salts, and liquids for leaf feeding; gaseous ammonia which basically represents nitrogen plus energy that is now transferable to plant metabolism; and pulverized native rock products such as phosphate rock, limestone, dolomite, glauconite, granite, and other agstones. At least half of these materials are geologically derived and come within the interest of the economic geologist working with non-metallic or industrial rocks and minerals.

Consider one more principle which links rocks and their use as plant nutrients. In order for them to be most effective they should be sufficiently available for plant pick-up but not so easily soluble that they are quickly leached away, and for the sake of nutrition they should not be so soluble as to cause an unfavorable imbalance of nutrients. If agstone of the native-rock type is supplied, it must preferably be finely pulverized; then it simulates such natural materials as glacial flour, volcanic ash, or fine alluvial silt comprised of silicates (and carbonates) rich in a large variety of cations. The mineral and chemical alluviation at the Hunza Farm locality illustrates the natural replenishment of inorganic soil fertility.

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FIGS. 1-7, MARCH, 1961

OFFSHORE SHOALS IN AREA OF ENERGY DEFICIT[1]

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ABSTRACT

The coastal energy level off the Apalachicola River Delta (panhandle coast of Florida) appears to be adequate to handle approximately $2\times10^4 m^3$ of sand and coarse silt per year. The river, through much of its recent history, has probably been delivering approximately $5\times10^8 m^3$ of bed load per year. Over a 5000 year period, this projects to an excess of approximately $2.5\times10^9 m^3$. The beach ridges, barrier islands, and furrowed offshore shoals in the area may have been formed as severe storm waves redistributed this load. The amount of sand stored in these geomorphic features is estimated to be approximately equal to the projected 5000-year excess.

An energy-vs-load chart is presented as an aid in the evaluation of coastal features.

INTRODUCTION

For ıpproximately six years faculty members and graduate students at Florida State University have been investigating the coast and shallow offshore waters in the vicinity of the Apalachicola (i.e., Chattahoochee) River Delta of Florida. Part of this work has been reported by Vause (1959), Tanner (1959), Waskom (1958), and Brenneman and Tanner (1958). The present report is based in part on work done by Milton (1958) and Mullins (1959).

It is a pleasure to acknowledge the support provided, for this project, by the Research Council of Florida State University and the Coastal Petroleum Company.

Field methods and description of the area have been presented by Tanner (1959). The coast line (fig. 1) is one of zero to moderate energy (Price, 1955). The zero energy portion lies south and southeast of Tallahassee (vicinity of point 7, on the map), and the moderate energy portion stretches from about Mashe's Island (point C, on the map) westward. The river is introducing both wash and bed load, most of which is directed westward by the prevailing motion of the littoral currents. The wash load is settling in part near the mouth of the river and in St. George Sound (point 2) and is being carried in part out into the Gulf of Mexico, where it is apparently widely distributed. The bed load, consisting almost 100 percent of quartz sand, is being piled up in marshland ridges (points 6, on the map), beach ridges (straight black lines such as those at point 2), barrier islands (near points 1, 2, 3, 4, and 5), and offshore shoals (south of points 1 and 3).

It is the purpose of the present report to examine the offshore shoals and to suggest a relationship between rate of delivery of river load, coastal energy level, and the morphology of the study area.

MARSHLAND RIDGES

Three of these narrow, gently curving sand bodies are shown on the map (fig. 1). Several other examples, including a number of dubious instances, occur in the general area. Brenneman (1957) studied these features in detail and concluded that they are probably imperfectly-formed barrier islands.

BEACH RIDGES

These narrow, long, essentially straight sand bodies may be found in several places in the area (straight black lines in fig. 1). More than 100 beach ridges occur within the circle in figure 1. Waskom (1957) studied representative examples.

The ridges may be closely spaced over relatively large areas, as on St. Vincent island (point 2, fig. 1; for detail, see fig. 2) or rather widely spaced. They are generally only about 1 ft to 10 or 15 ft high and a few tens of feet wide at the base. Obvious on air photos, some of the ridges can be found on the ground only with difficulty.

Each ridge is a quartz sand body with poorly preserved internal structure, appar-

[1] Manuscript received March 21, 1960

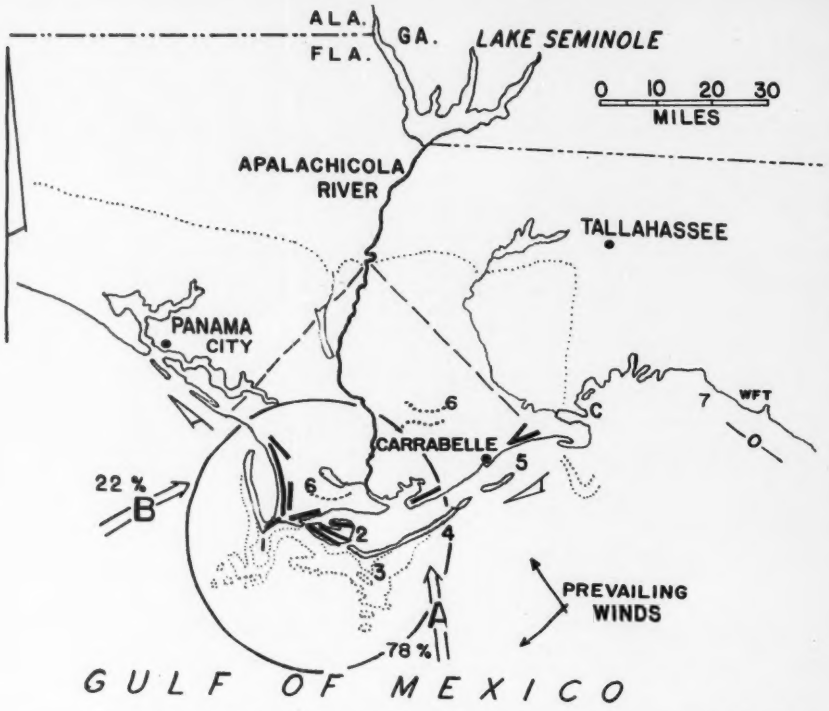

FIG. 1.—Map of the area of the Apalachicola River Delta (largely within the circle). Numbered points of interest are· 1. Cape San Blas, 2. St. Vincent Island, 3. Cape St. George, 4. St. George Island, 5. Dog Island, 6. Marshland ridges, 7. Zero energy shore; A. and B. Hurricane paths; C. Chenier. The short broad black lines indicate the location and orientation of beach ridges. The dotted lines offshore are approximate 18 ft and 30 ft isobaths, respectively.

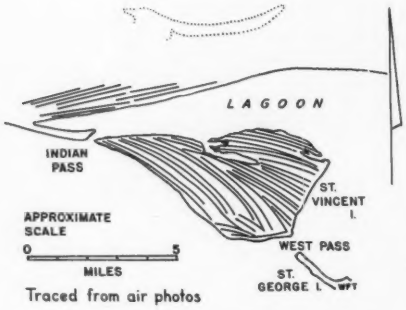

FIG. 2.—Detail map of St. Vincent Island, showing the more important beach ridges.

ently resting on a sand base. For this reason they are beach ridges instead of cheniers (fig. 3). The taller ridges are devoid of tree cover, although trees grow well in the lower, flat areas between the ridges. The more subtle ridges have a well-developed tree cover except where recent logging has been carried out. It is possible that the highly permeable sands of taller ridges do not retard downward percolation of rain water sufficiently for seedlings to develop root systems.

Waskom (1957, 1958) found no detectable difference in sand samples collected from beach ridge crests and from the sand flats in between ridges. The mean diameter for

FIG. 3.—Beach ridges (on sand base) and a chenier (on clay base). Trees grow on the chenier, and on the more subtle beach ridges, but generally do not grow on the taller beach ridges.

crest samples was 0.217 mm (standard deviation 0.041); the mean diameter for swales was 0.226 (standard deviation 0.053). The phi deviation measure, $D_k \approx \sigma$, was 0.40 for both crest and swale samples; the Trask coefficient of sorting, S_o, was 1.17 and 1.18, respectively. In other words, the sand within the ridges is essentially the same as the sand flooring the flat areas between the ridges. Furthermore this sand is essentially the same as that occurring offshore but close to the beach in the same general area.

The sequence of beach ridges on St. Vincent island and landward from Indian Pass (fig. 2) numbers approximately 50. These ridges are all either parallel or subparallel with the modern coast. They also all stand at about the same elevation and therefore all probably date from the time when sea level attained its present position. This critical moment has been given as approximately 5000 years ago by LeBlanc and Hodgson (1959) and as approximately 3500 years ago by Gould and McFarlan (1959). A calculated rate of development would be, therefore, approximately one ridge per 70 to 100 years. The lengths of the ridges are not uniform, however, and from this argument alone one would probably hesitate to reason that the rate of accretion has been constant.

The volume of sand included in the beach ridges of the area is approximately 200 million cubic feet (about 6,000,000 cubic meters; much less than 1 percent of a cubic mile). A larger quantity of sand is present in the sand sheet on which the beach ridges rest.

Because the relief on the ridges is slight (caused, in turn, by the low energy level along this part of the coast) and because the materials occuring on the ridges is practically identical with the material in the sand sheet beneath the ridges, buried features of this kind probably could not be identified, as such, by ordinary subsurface means.

CHENIERS

Only one chenier is known in the general area; its location is shown at point C in figure 1. The volume of sand is insignificant. The basic difference between beach ridges and cheniers is illustrated in figure 3.

BARRIER ISLANDS

Brenneman (1957) studied sands from St. George island (fig. 1, points 3 and 4) and St. Joseph spit (fig. 1, north of point 1). From 32 samples he determined mean grain sizes of 0.25 mm for St. George Island and 0.24 mm for St. Joseph spit. The phi deviation measure, $D_k \approx \sigma$, was 0.45 and 0.36 respectively, indicating that the more westerly samples were better sorted.

It is estimated that the chain of barrier islands inside the circle (fig. 1) and im-

FIG. 4.—Profile across representative beach ridges (solid black), compared with typical profiles across offshore shoals (dotted, dashed, and continuous lines). Both are drawn to the same scale.

mediately to the east of the circle contains 1.7×10^9 cubic meters of sand (about one-half cubic mile).

OFFSHORE SHOALS

Three well-developed shoals occur in the general area (see fig. 1; one each at points 1 and 3 and a third southeast of point 5). A single shoal (the one south of St. George lighthouse; point 3) was studied in detail by Milton (1958) and Mullins (1959). A map of this shoal, taken from U.S.C.G.S. Chart 1262, appears as figure 5.

The map is characterized by roughly linear or gently curving shoals and deeps which have a crude parallelism with the shore line. They are not, however, submerged beach ridges, as can be seen in figure 4 where beach ridges (solid black) are compared with representative offshore shoal profiles (solid, dashed, and dotted lines).

The gulf floor sands are finer near the beaches and become coarser seaward. Superimposed on this seaward trend is a local change in grain size which is apparently controlled by the sea-floor topography. However, unlike what one might expect, the finer sands occur on the highs and the coarser sands in the lows. Twelve sand samples from relatively shallow water averaged 0.285 mm (mean diameter); 14 samples from troughs averaged 0.317 mm (mean diameter). Additional samples from intermediate depths (that is, neither shoals nor troughs) range from an average mean diameter of 0.22 mm near shore to an average mean diameter of 0.44 mm at 7 to 10 miles offshore.

Unfortunately, a simple direct comparison of trough-versus-shoal samples fails to make a distinction between them. This is because of the rather wide variability in addition to the presence of the general seaward coarsening in the area. However, Mullins (1959) was able to use a modified system of run analysis which permitted study of the data. He used four sample profiles, consisting of seven to eleven samples each, taken along lines running from 1 mile to approximately 12 miles offshore. These parallel lines were approximately 1 mile apart. Water depths were recorded at each sample site, and no other depth data were used in construction of the profiles. For each graph, midpoints of imaginary lines between geographically adjacent values were joined. This produced a "median profile" for each parameter studied (such as grain diameter). Each sample value was compared with the median profile and recorded as a minus mark if it was numerically higher than the profile value and as a plus mark if numerically lower. Mullins recorded a typical water depth "run" as follows:

$$-+-++-+-+.$$

This meant that the first sample had a value (in this case water depth) numerically greater (that is, deeper) than the median profile, the second was shoaler, the third deeper, etc. Four such profiles were prepared for water depth, four for median grain size, four for sorting, four for $CaCO_3$ content, and four for heavy mineral percentages. The various profiles were then compared, two at a time, as follows:

Profile A:

Water depth:	$-+-++-+-+$
Diameter:	$---+-+--$
Differences:	$\times \quad \times$

The differences (marked by x's) were noted, counted, and compared with the similarities. In this example there were two differences and seven similarities. Data from 38 sample stations, arranged in four parallel lines, were examined in this fashion.

Using a significance level of 0.05 (that is, any value below 0.05 is considered significant), Mullins found the following probabilities for the notion that the indicated similarities could occur by chance alone:

(1) Water depth and median grain diameter: 0.00117.
(2) Water depth and sorting: 0.000124.
(3) Water depth and $CaCO_3$ percentage: 0.00003.
(4) Water depth and heavy mineral percentage: 0.36693.

In other words, heavy mineral distribution does not seem to be controlled by local bottom relief. On the other hand, median diameter, sorting, and $CaCO_3$ percentages do appear to be so controlled. An examination of sample station data reveals that the sediments in the troughs have larger grain diameters and poorer sorting, whereas the

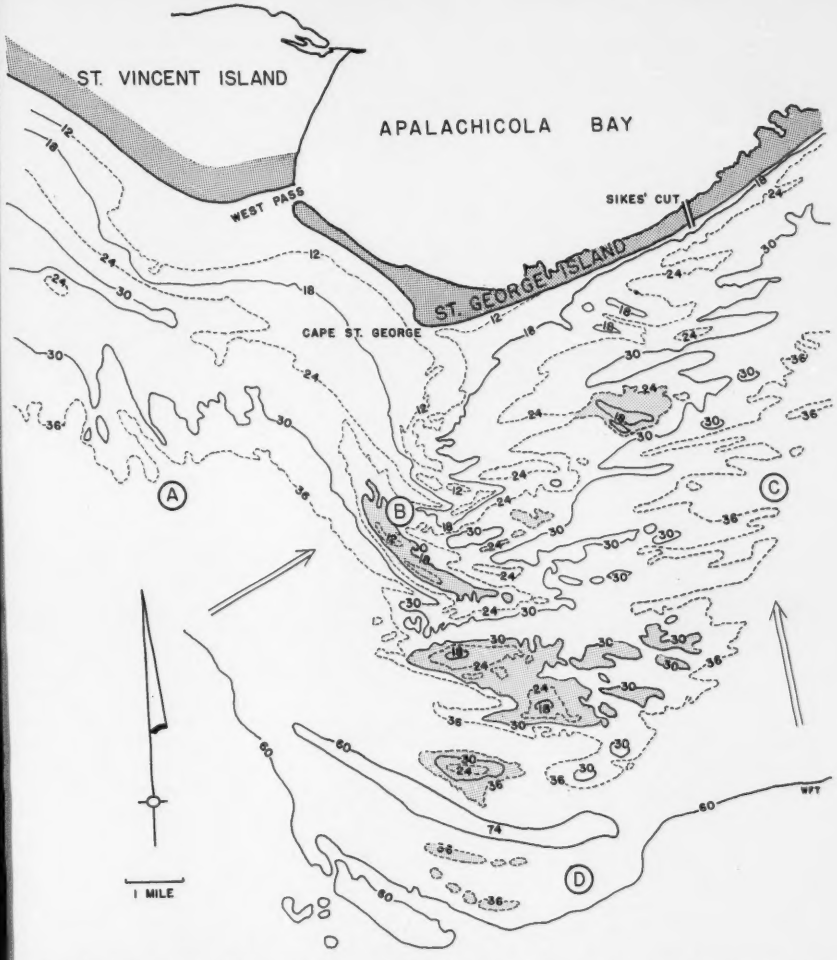

FIG. 5.—Map of the offshore shoal area south of Cape St. George (see fig. 1 for location). Isobaths shown are for 12, 18, 24, 30, 36, and 60 ft. The furrowed appearance of the shoal is clear. Alignment of linear features is essentially parallel with the coast, and at right angles to known hurricane paths. Two different orientations can be seen: one at A and B, a second at C, and a combination at D. Average hurricane paths are shown by double-shafted arrows. (Based on U.S.C.G.S. Chart 1262.)

sediments on the shoals have smaller grain diameters and better sorting. These results are shown diagrammatically in figure 6. In addition, there is more $CaCO_3$ in the troughs.

Apparently removal of fines from the shoals by winnowing is not as effective in the study area as some other process.

This shoal area is estimated to contain 1.0×10^9 cubic meters of sand (approximately 0.3 cubic mile). The more westerly shoal area is estimated to contain approxi-

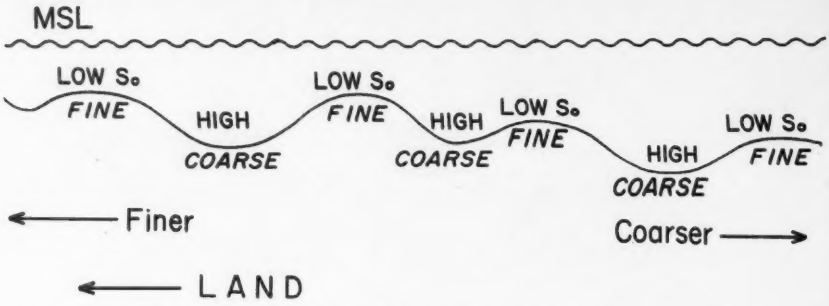

FIG. 6.—Representative profile across an offshore shoal area, showing that finer sands exhibiting better sorting occupy the shallow portions, and coarser sands having poorer sorting occupy the deeps or troughs. The sands also become coarser, in general, seaward.

mately 0.5×10^9 cubic meters of sand (approximately 0.15 cubic mile).

ORIENTATION

The detailed map (fig. 5) shows two distinct orientations of shoals and troughs in the shoal area. Two examples of one orientation occur near "A" and "B," and two examples of a different orientation occur near "C" and "D." These alignments should be compared with wind data presented on the map in figure 1. Prevailing winds are generally easterly and are consistent with the dominant westward littoral drift. Florida panhandle hurricane paths, on the other hand, are southerly or westerly (note double-shafted arrows); of nine well-documented paths, two were southwesterly (1917, 1929), one was southeasterly (1926), and the rest were southerly (1896, 1916, 1936, 1941, 1950, 1953). The average of the southwesterly paths is given in figure 1 at "B" (22 percent), and the average of the six other paths is given at "A" (78 percent). These two arrows are duplicated in figure 5. It may be observed that hurricane paths appear to be at right angles to the trends of the individual troughs and shoals (Guilcher, 1958, p. 182; Schou, 1952; Lewis, 1931, 1938).

ENERGY LEVEL

The Florida panhandle coast is characterized throughout most of its length by moderate energy (A zero energy sector, southeast of Tallahassee, is shown in figure 1). Moderate energy is defined, for the purposes of this study, as marked by annual mean breaker heights between 10 and 50 cm. The annual mean breaker height reported (Helle, 1958) for Cape San Blas (fig. 1, point 1) is approximately 13 cm, increasing westward.

Figure 7 has been drawn to permit a comparison of coastal energy in terms of breaker height with sand supply. This chart, based on data from Helle (1958) and Hall (1953), was originally prepared to allow a geomorphic evaluation of certain coasts in line with the concept of the equilibrium beach (Tanner, 1958). It was presented informally at the Summer Institute in Marine Geology at Florida State University in June 1959. Geologists who participated in that discussion were of the opinion that the chart would be more useful if a measure of unidirectional energy could be obtained. Subsequently, the Beach Erosion Board has indicated that it may be possible for future surf statistics reports to be organized so that unidirectional energy can be computed more easily.

At about the same time Savage presented a similar chart (Savage, 1959, fig. 4) incorporating the same basic idea. Despite the defect in the present chart (fig. 7; the indiscriminate mixing of wave attack directions), the equilibrium lines in the two diagrams are essentially the same.

Not all coasts should plot on the equilib-

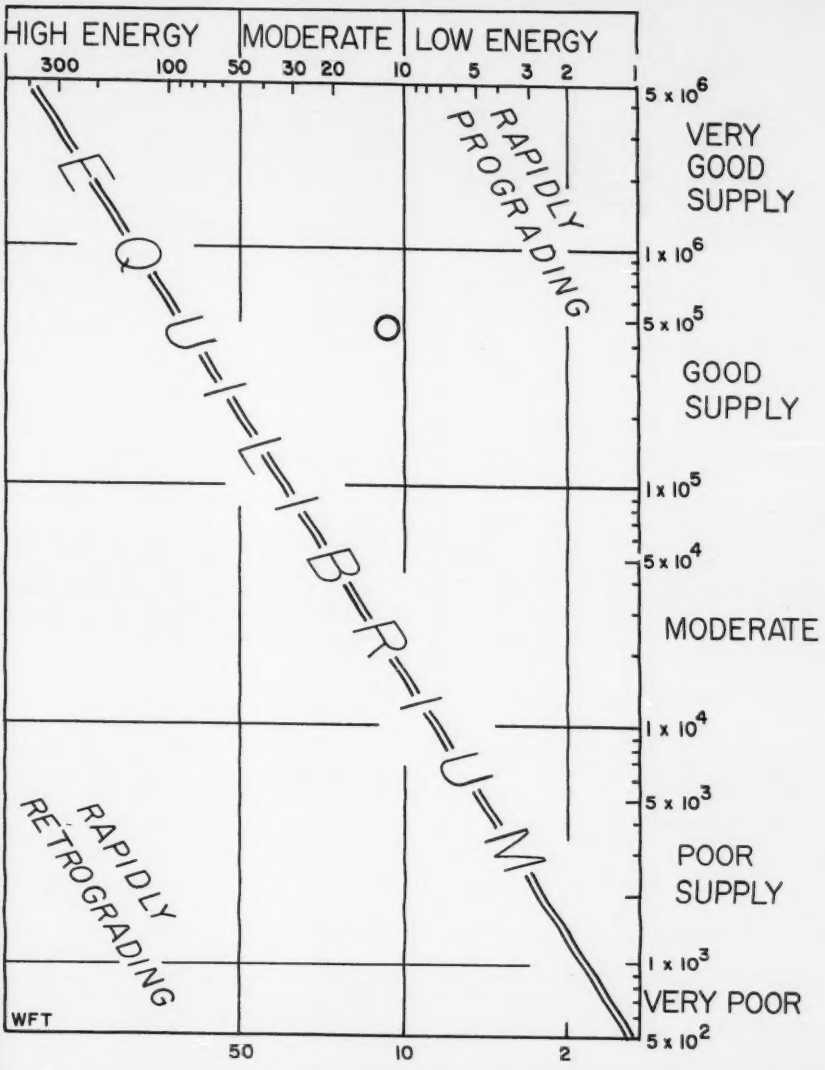

FIG. 7.—Shoreline equilibrium chart for evaluation of various geomorphic features. Wave energy, in average breaker height in centimeters, is shown across the top on a logarithmic scale. Sand supply, in cubic meters of littoral transport per year, is shown along the side on a logarithmic scale. The circle indicates the plot for the Apalachicola River Delta area, where the amount of material available (from the river) is obviously too much for the waves and currents to handle. This chart is based on data published by Hall (1953) and Helle (1958).

rium line. Any locality that falls in the upper right hand corner of the chart would be expected to have a coast marked by relatively obvious progradation. The seaward advance of the shore line might be attributed to the introduction of "bed" or traction load more rapidly than the waves and currents could handle it. If that load is river borne, then a cuspate delta of some kind should be formed.

It is estimated that the Apalachicola River, prior to the construction of a series of dams, delivered approximately 5×10^5 m³ of load per year (estimate based on figures furnished by U. S. Army Engineers). The reported energy level, however, requires, for a shore line which does not shift its position, an introduction of no more than approximately 2×10^4 m³ of bed load per year. The amount of river sand and silt delivered annually across the delta seems to be too much by a factor of more than 10. This excess is, apparently, used to build the offshore shoals and troughs, and a minor part is in turn moved onshore to form beach ridges during periods of high waves.

With the construction of several dams, the supply of river-borne sand should diminish greatly.

WAVE REFRACTION

Normally one expects refraction of waves in the vicinity of a shoal to concentrate energy upon that shoal and therefore to tend to remove it. In the study area wave refraction occurs according to expectation. In fact, discrimination among hurricane paths may not be necessary, inasmuch as refraction alone would probably account for the varying orientations of individual troughs and shoals. But the energy level along this segment of the coast is not high enough to permit effective attack on the shoal areas. Storm waves, altered by refraction, may rearrange the sand contained in the shoals, and part of the sand is undoubtedly being moved westward, but there is no reason to expect wave action at present energy levels to eliminate the shoal areas.

CONCLUSIONS

The total volume of sand estimated to be contained in the beach ridges, barrier islands, and offshore shoals of the area is of the order of 10^9 m³ (actual estimate: approximately 3.5×10^9 m³). The river appears to have been delivering approximately 4.8×10^5 m³ more sand per year than the coastal energy can accomodate. Over a period of 5000 years this represents an estimated excess on the order of 10^9 m³ (actual estimate: approximately 2.5×10^9 m³). Therefore, it seems that the sand of the area has accumulated essentially during the last still-stand of sea-level because of the inability of waves and currents to handle the load presented annually by the river.

Inasmuch as the coastal energy level is not adequate for transportation of the load, the geomorphic features of the area may be caused in large part by marine redistribution of the load. That is, beach ridges are formed (during exceptionally severe weather; Guilcher, 1958, p. 42) by the piling up along the beach of part of the excess sand; the offshore shoals are modified in much the same way. Since the shoals are built in deeper water, they show a much greater modification than do the beach ridges. It is suggested that the arrangement of finer sands on the shoals with coarser grains in the troughs is caused by a landward piling up of sand (during exceptionally severe weather), with the taller, finer-grained portions representing the areas of maximum massive wave transportation and the lower (that is, deeper), coarser-grained portions indicating a lag effect. Because the off-shore shoals are affected by deeper-water waves over a much longer period of time, it is thought that detailed features (such as are found on the beach ridge plain) are either not formed at all or are smoothed out relatively quickly.

It is possible that a similar mechanism accounts for certain other shoal areas such as those off of the western coast of peninsular Florida and off of the eastern coast of North Carolina.

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FIGS. 1–3, MARCH, 1961

COMPARATIVE EFFICIENCIES OF SIZE ANALYSIS BY HYDROMETER AND PIPETTE METHODS[1]

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ABSTRACT

A large sample of silt and clay was divided into nine sub-samples with concentrations increasing from 3 g/l to 25 g/l. These sub-samples were first subjected to the hydrometer analysis after which they were shaken and re-analyzed by the pipette method. The results of the two analyses were then compared.

Within a moderate range of silt and clay concentration (6 to 24 g/l), the analyses gave similar results for the 5ϕ through 9ϕ size-grades. With concentrations of less than 6 g/l, the pipette analysis was superior; with concentrations greater than 24 g/l, the hydrometer analysis was more efficient. Within the range of concentrations studied, however, the pipette method gave better over-all results.

INTRODUCTION

In the past several decades, hydrometer analyses have been used increasingly for sediment-size determinations. Some workers use any of the numerous hydrometer analysis methods for samples rich in silts and clays but use the pipette analysis for samples of low silt-clay concentrations. Other workers use one method exclusively.

Since the hydrometer analysis was presented by Bouyoucos in 1927, it has often been compared with the pipette method in order to prove or disprove its validity as a procedure for particle-size determination. However, until Day (1950), sound physical basis for the hydrometer method was not provided. These comparisons, however, have always dealt with one pair of analyses on many different soil samples rather than with a number of analyses applied to the different concentrations of the same sediment.

The present study was undertaken to determine the differences, if any, that might exist between size-grade results obtained by using the hydrometer and those obtained by using the pipette method of Krumbein and Pettijohn (1938, p. 166–172). The test series was conducted with varying concentrations of suspended sediment (3 g/l to 25 g/l). A Recent marine sediment from Puget Sound was selected at random from the sediment file of the Department of Oceanography, University of Washington, for the purpose of the test program.

PROCEDURE

Nine sub-samples were separated from a large sampling of silt and clay. In order to remove all salts, each sub-sample, after slaking in distilled water, was shaken vigorously and centrifuged at 1700 rpm for 40 minutes. The supernatant fluid was decanted from the centrifuge bottles and replaced by approximately 300 ml of distilled water containing 0.1 g/l of Marasperse N (sodium lignosulfonate). The samples and peptizer were shaken for dispersion in a wrist-action shaker for 20 minutes and then were transferred to 1000-ml cylinders for analysis. The nine sub-samples were prepared so that the final concentrations ranged from 3 g/l for sub-sample no. 1 to 25 g/l for sub-sample no. 9. The hydrometer analysis was first run on each of the nine sub-samples; these were reshaken and then the pipette analysis was run. The settling velocities of the particle sizes in both cases were computed according to Stokes' Law.

The objective was to determine under what range of silt and clay concentrations the results of the two methods were comparable and through what range of concentrations each method was effective.

DISCUSSION

The results of the analyses by both methods are given in table 1, the data being given

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TABLE 1.—*Cumulative percentage of size fractions determined for varying concentrations of sediment suspension*

Sub-sample no.	Concentration g/l	Method	5.38φ*	6φ	7φ	8φ	9φ	10φ
1	3.005	Hydrometer	18.00	33.50	48.00	55.00	58.80	66.70
		Pipette	33.28	50.50	65.30	75.20	81.40	86.00
2	6.292	Hydrometer	29.80	49.20	62.90	65.70	70.00	76.50
		Pipette	36.55	52.20	70.80	80.80	86.30	90.50
3	8.898	Hydrometer	36.00	51.30	63.80	69.40	76.50	80.00
		Pipette	34.28	51.80	70.00	78.50	83.80	88.50
4	11:977	Hydrometer	36.00	49.90	68.10	74.10	78.90	83.00
		Pipette	35.90	53.50	67.60	78.70	84.00	88.50
5	15.108	Hydrometer	42.00	58.10	69.90	75.50	79.80	85.00
		Pipette	31.77	49.20	66.70	76.10	81.50	86.20
6	17.602	Hydrometer	30.50	49.30	65.90	74.90	80.60	84.50
		Pipette	33.80	47.00	69.20	77.10	83.00	87.50
7	20.815	Hydrometer	34.00	49.90	67.50	76.00	79.90	85.60
		Pipette	32.19	49.00	66.60	76.90	81.70	86.70
8	24.090	Hydrometer	24.40	49.50	67.00	74.50	81.00	85.50
		Pipette	35.70	52.00	69.70	79.80	85.00	90.30
9	25.056	Hydrometer	32.00	49.00	70.00	76.90	82.90	86.00
		Pipette	23.35	38.50	56.80	64.70	70.00	74.50
Mean		Hydrometer	31.41	48.86	64.79	71.33	76.49	81.42
		Pipette	32.98	49.30	66.96	76.42	81.85	86.52

* After temperature adjustment, the 5φ size was found to be 5.38φ.

as cumulative weights by percent in Wentworth sizes (using Phi notation). Figure 1 presents the cumulative frequency curves obtained from each of the sub-samples. This figure shows the change in the curves of the sub-samples as the concentration of sediment increases.

Figure 1 also shows the poor correlation between hydrometer analysis no. 1 and all other hydrometer analyses and between pipette analysis no. 9 and all other pipette analyses. On the other hand, all other cumulative frequency curves obtained from both types of analysis exhibit close resemblance. A gradual transition zone can be observed between hydrometer analyses nos. 1 through 4, but beyond no. 4 the hydrometer results appear consistently similar to those obtained by the pipette method. This gradual transition with increasing concentration is not observed in the curves representing results of the pipette analyses; the curves of the first eight sub-samples are quite similar, but the curve for sub-sample no. 9 is significantly different.

Figure 2a shows the average cumulative frequency curve obtained by the hydrometer analysis as compared to that of the pipette method. In the coarse, medium, and fine silt range (5 through 7φ), the pipette and hydrometer analyses yield similar results; the curves are divergent in the very fine silt range (7 to 8φ), whereas they are parallel in the clay sizes.

A 5 percent confidence interval was established around each of the curves in figure 2a. This interval was considered to be the minimum probability level necessary for rejecting any cumulative frequency curve obtained from the analyses. Thus, any curve that fell within this interval was accepted and used in the construction of a more repre-

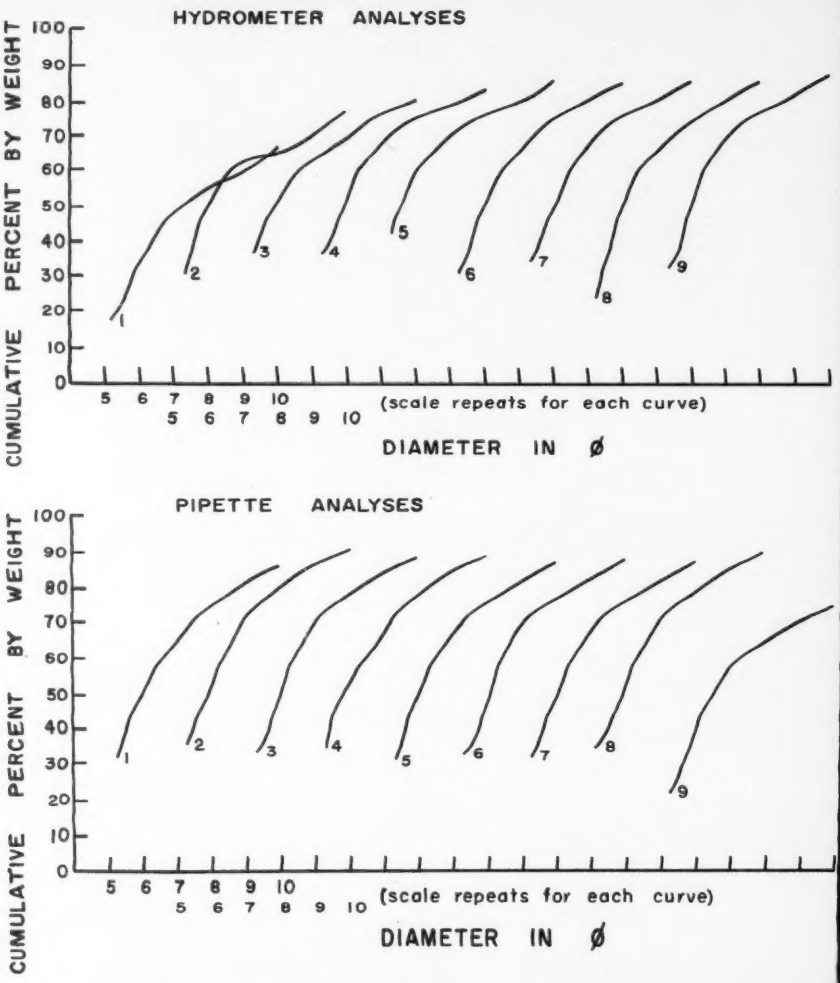
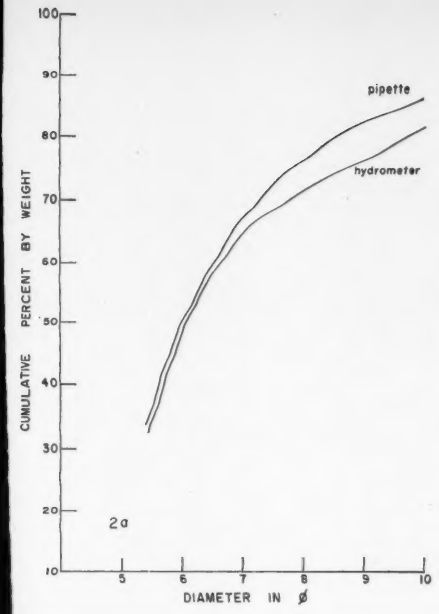
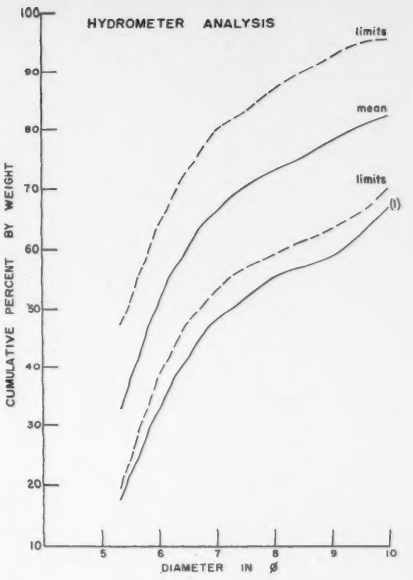


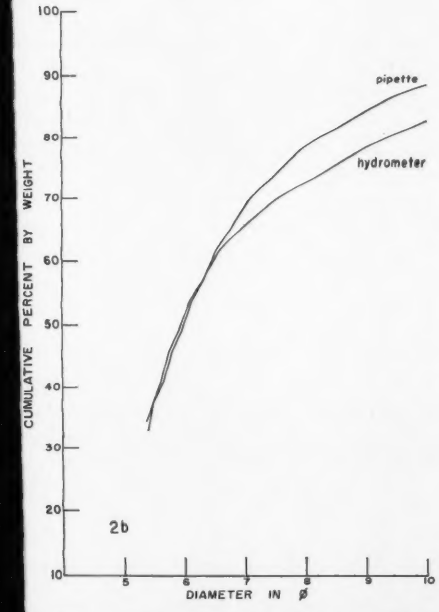
FIG. 1.—Evolution of cumulative curves with increasing silt-clay concentrations. The lowest point plotted for each curve is the measured percentage at the 5.38ϕ size.

sentative cumulative frequency curve of this sampling (fig. 2b); any curve not encompassed by this interval was rejected. Figure 3 shows that the curve from hydrometer analysis no. 1 and the one from pipette analysis no. 9 failed to fall within their respective 5 percent confidence intervals.

The difference between the curve for hydrometer analysis on sub-sample no. 1 and all the others is probably caused by the low silt-clay concentration (3 g/l) in this particular sub-sample. Because of this low concentration, changes in density with time were slight, causing variations on the hy







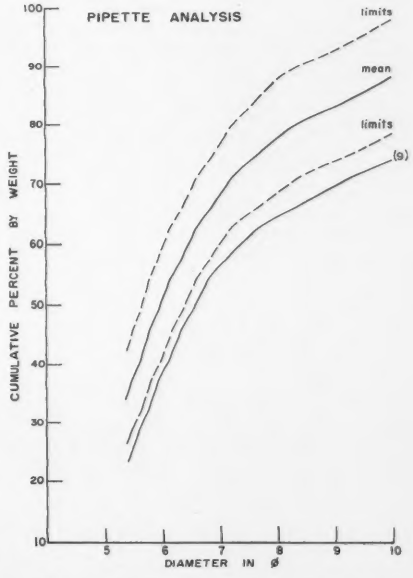


FIG. 2.—Comparison of mean cumulative curves obtained by pipette and hydrometer analyses. 2a is based on all original analyses; 2b is drawn from statistically valid analyses.

FIG. 3.—Mean cumulative curves of each method of analysis showing the limits of a 5 percent confidence interval. Curves (sub-samples no. 1 and no. 9) not falling within this interval are plotted.

drometer scale in the range beyond 6ϕ to be negligible and thus difficult to detect.

It is more difficult to account for the abnormal cumulative frequency curve of pipette analysis no. 9. It was noted, however, that the filling-time of the pipette increased with increasing sediment concentration; for sub-sample no. 9, the large amount of suspended sediment increased the viscosity of the fluid to the point where the filling-time was almost twice that for sub-sample no. 1. This may be an important factor in the coarse sizes, especially where the time in pipetting is relatively long compared to the time required for the particles to settle.

If curves 1 and 9 are disregarded as being non-representative of the silt and clay proportions in the sampling, two corrected average cumulative frequency curves can be computed from curves 2 through 8. This will allow comparison of average results of the pipette and hydrometer analyses within the silt-clay concentrations ranging from 6 to 24 g/l. The corrected average cumulative frequency curve for each method of analysis is shown in figure 2b; these new curves can be considered as being better representations of the silt-clay contents of this particular sampling of sediment.

Student's t-test can now be applied for a comparison between the corrected mean curves of each analysis method, the null hypothesis stating that the average cumulative frequency curves obtained by each method are significantly the same. This test showed that through 7ϕ the null hypothesis should not be rejected; in the 8 and 9ϕ size-grade, the differences between the curves are on the borderline of rejection; for 10ϕ the hypothesis is to be rejected. In other words, both methods of analysis give similar results from 5 to 7ϕ; results may or may not be comparable for 8 and 9ϕ; and results are statistically incompatible for 10ϕ.

The sudden rise in the cumulative frequency curve for pipette analysis between 7 and 8ϕ (fig. 2b) may be the result of slight flocculation of the clay-size particles. This could well be the case since the pipette analysis was not run until after completion of the hydrometer analysis; thus, when the 8ϕ aliquot was pipetted, the sediment had been in the cylinder for a much longer time than when the 8ϕ hydrometer reading was taken. At the end of the analyses there was a small amount of flocculated sediment.

In evaluating the statistical analysis it should be noted that at no size-grade do the curves represented in figure 2b deviate from each other by more than 5.5 percent.

Conclusions

On the basis of this study, the following conclusions can be drawn:

1.—The accuracy of the hydrometer method improves with increasing concentrations of silt and clay. This method is not practical with concentrations of less than 6 g/l and it gives only fair results with concentrations of less than 12 g/l (fig. 1).

2.—The pipette method does not give accurate results with concentrations higher than 24 g/l; therefore, the pipette method should not be used without further evaluation of its efficiency at high concentrations.

3.—In moderate ranges of fine-fraction concentrations (6 to 24 g/l), analyses by both pipette and hydrometer yield essentially similar results for size-ranges between 5 and 9ϕ. Statistically, the results are different for the 10ϕ size-grade.

4.—Within the 6 to 24 g/l range, the pipette method shows better degree of consistency and closer clustering of results than does the hydrometer method (figs. 1 and 3).

ACKNOWLEDGMENTS

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FIGS. 1–11, MARCH, 1961

RELATIONS OF SETTLING VELOCITY OF SAND SIZED SPHERES AND SAMPLE WEIGHT[1]

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ABSTRACT

The fall velocities of the boundaries of a series of well sorted samples of sand sized glass spheres were determined in a modified Emery type settling tube for the purpose of measuring the changes in mass fall velocities with changes in sample weights. Fall velocities of the faster falling, larger diameter spheres forming the leading boundary in each sample were found to increase with sample weight. Fall velocities of smaller spheres forming the slower or trailing boundary were found to decrease with increasing sample weights. Over the median diameter range of 0.784 to 0.383 mm these velocity changes appeared to be relatively independent of particle diameters, but at smaller median diameters the relative changes in velocity increased with decreasing size. From the weight-velocity relationships, it was shown that fall velocities achieved by masses of spheres depend upon the amount of sample used. Boundary velocities were attributed to certain particle diameters to provide a measure of the effects of the falling system on given sized spheres. It appeared further that the velocity of a given particle settling in a sample depends upon the size limits and the sorting of the sample. It was concluded that settling methods of analysis of sands do not give an accurate picture of size distribution in terms of sedimentation radii if the fall of the particles creates turbulence in the system.

INTRODUCTION

The visual accumulation type settling tube was proposed by Emery (1938) as a rapid means of determining the approximate size distributions of fine sands. The apparatus and technique are relatively simple. A sample of sand is placed in the top of a column of water and the heights of accumulation of sediments at the bottom are recorded visually at times predicated on the terminal fall velocities of the various sized particles. The analysis yields results in terms of volumes of sediments having hydraulic properties or values within established limits to which the term sedimentation radii (Wadell, 1934, p. 281) has been applied.

The basic criterion used in settling tube analyses is fall velocity of the particles under given conditions. Ideally, in the absence of wall effects or interferences between the particles making up the sample, each particle achieves a terminal fall velocity after a very short distance of fall, and rate of accumulation at the bottom of the tube has been found to be reproducible (Poole, Butcher, and Fisher, 1951). The resulting analysis is capable of being very accurate if fall velocities applicable to the sediments are known. A number of investigators have attempted to apply single grain fall velocities of sands to settling in Emery type tubes. It has been found, however, that practical quantities of sand fall at velocities appreciably different from those of individual grains. Poole (1957, p. 465) recognized that fall of a group of sand sized particles was from 10 to 15 percent faster and in general he recognized an error in the resulting analysis of about one-eighth phi unit due to the increase. Report No. 11 (1957, p. 34)[2] established correction factors for single grain velocities in certain settling tubes ranging up to 20 percent to compensate for the increases observed in group settling velocities. It became apparent to these investigators, as well as to others, that the familar laws of single particle fall do not necessarily apply when particles fall as a group.

The problem in settling of sands is, therefore, one of determining just what fall velocity should be attributed to a given sized grain or size interval. The investigation described in this paper was undertaken to measure the limiting settling velocities of closely sized samples of glass spheres in an effort to determine the relations between

[1] Manuscript received April 10, 1960.

[2] Numbered "Reports" are listed under Subcommittee on Sedimentation in the list of References.

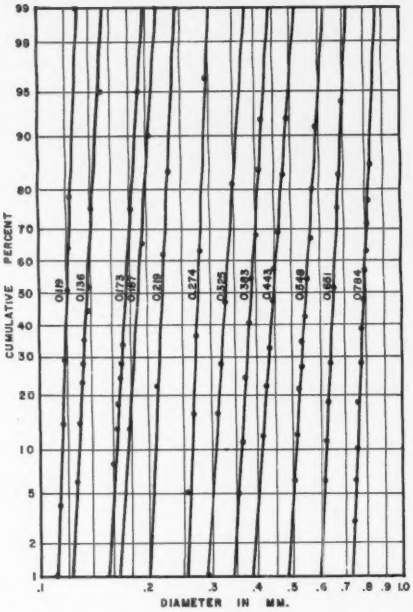


FIG. 1.—Cumulative frequency curves of samples of glass spheres.

settling velocities and quantity of sample. The data will be viewed primarily from the aspects of determining calibration of standard fall velocities.

SAMPLES

The samples used in determining group fall velocities were commercial quality glass spheres. The primary considerations in selecting the beads were to secure a number of samples of spheres having uniform densities, equivalent sorting, gradational sizes, and whose median diameters ranged over the interval of 1.00 mm to 0.10 mm. Size limits of the samples were established by sieving and using the fractions retained on each sieve as a sample. The stock beads contained irregular particles of glass, and it was necessary to remove these in order to obtain samples of uniform spherical qualities. Irregular beads were removed from the coarser samples by rolling the beads down an inclined plane. The free rolling beads were collected and assumed to be spherical. Finer samples were not amenable to this treatment, so attempts were made to remove irregular beads in those samples by settling. A portion of each sample was introduced in the settling tube, and the few particles falling entirely free of the greater part of the sample were withdrawn at the bottom of the tube. The greater part of the beads so removed were found to be larger than the average beads in the distribution. Examination of the samples using a petrographic microscope revealed that the spherical properties of the samples were practically uniform excepting the 0.136 mm sample which contained appreciable amounts of irregular beads and chunks of glass.

Cumulative frequency curves, shown in figure 1, were prepared from optical measurements of 300 random spheres in each sample, and pertinent data from figure 1 are recorded in table 1. Each sample had a very small range in size, not exceeding 0.25 phi unit, and there were minor overlaps between the curves of the samples. The average sample had a coefficient of sorting of 1.03 and was practically unskewed. The average kurtosis is 0.28. The median diameters will be used for convenience in referring to the samples.

The specific gravities of representative portions of each sample were determined using a pycnometer and distilled water. Corrected specific gravities are given in table 2. Average specific gravity is 2.462, and the maximum variation from the average is about 3.25 percent. While it is believed that real differences between the samples may have existed, they were probably small compared to the experimental error in the technique. For purposes of the following discussion, specific gravities of the samples are considered to be uniform.

Quantities of the samples appropriate for velocity determinations were established by making a series of pilot runs. Weights to be used were chosen as follows: 0.25, 0.50, 0.75, 1.0, 2.0, 3.0, 4.0, and 5.0 gm. Stock samples of 0.25 gm and 1.0 gm were obtained by microsplitting so that the desired experimental weights could be compounded from these quantities.

TABLE 1.—*Characteristics of samples*[1]

Sieve Opening mm	Median Diam. mm	Percentile				S_o	SK	K
		10	25	75	90			
0.701	0.784	0.745	0.765	0.818	0.830	1.03	1.02	0.31
0.589	0.651	0.615	0.631	0.672	0.686	1.03	1.00	0.29
0.495	0.548	0.510	0.525	0.570	0.587	1.04	1.00	0.29
0.417	0.443	0.410	0.426	0.462	0.480	1.04	1.00	0.26
0.351	0.383	0.358	0.370	0.398	0.410	1.04	1.00	0.27
0.295	0.325	0.302	0.314	0.340	0.352	1.04	1.01	0.26
0.246	0.274	0.262	0.267	0.282	0.287	1.03	1.00	0.30
0.208	0.219	0.208	0.212	0.225	0.230	1.03	1.00	0.30
0.175	0.187	0.174	0.180	0.195	0.201	1.04	1.00	0.28
0.147	0.173	0.164	0.166	0.180	0.187	1.04	1.00	0.26
0.124	0.136	0.128	0.132	0.141	0.145	1.03	1.01	0.26
0.104	0.119	0.115	0.117	0.122	0.125	1.02	1.01	0.25

[1] Taken from figure 1 and from the following calculations:

$$S_o = (P75/P25)^{1/2}$$
$$SK = P25P75/M^2$$
$$K = (P75 - P25)/2(P90 - P10)$$

APPARATUS

The group fall velocities were determined in a modified settling tube assembly similar to that described by Emery (1938) and Report No. 11 (1957). Figure 2 shows the essential parts and dimensions of the apparatus. The main tube was mounted on a stand to provide maximum stability and to permit plumbing of the entire column. Measured ranges of 50 and 100 cm were marked on the main glass tube, with the upper mark being placed well below the introductory mechanism to minimize the initial effects of turbulence accompanying release of the sample. Loading involved closing the upper hinge clamp and placing the sample directly into the upper section which contained water. The sample was then stirred with a glass rod to dispel bubbles and the water level refilled to a standard level. Release of the hinge clamp dropped the sample. In practice the sample was permitted to settle directly to clamp B. Recovery of the sample involved closing clamp A, loosening the glass joint, opening clamp B, and flushing the sample from the tube and hose by a directed stream of water. The recovery mechanism was then refilled and connected back into the sedimentation column. No significant loss of sample was incurred using this technique.

The apparatus and the samples were cleaned with a sulfuric acid-potassium dichromate solution to prevent the spheres from sticking to the tube wall and to minimize clumping of the spheres in the introductory mechanism.

All velocities were determined in distilled water at a standard temperature of 27 deg Centigrade. Temperature was checked before and after running a series of samples and while running the samples if room temperature varied. Water temperatures were carefully standardized by thorough mixing both in the settling tube and reserve water supply, and sufficient time was allowed to permit bubbles to dissipate in the main tube.

SAMPLE FALL AND TIMING PROCEDURE

The determination of group fall velocities required the measurement of fall times of

TABLE 2.—*Corrected specific gravities of samples*

Median Diameter (mm)	Specific Gravity
0.784	2.539
0.651	2.478
0.548	2.484
0.443	2.481
0.383	2.469
0.325	2.470
0.274	2.454
0.219	2.378
0.187	2.436
0.173	2.468
0 136	2.454
0.119	2.459

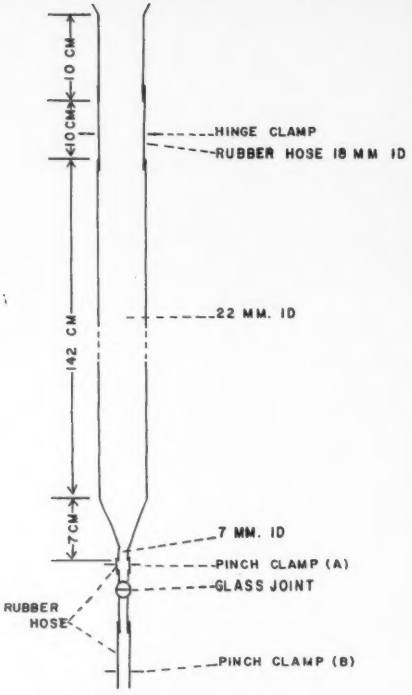


FIG. 2.—Modified Emery settling tube.

significant quantities of spheres in each sample over a known distance of fall. Observations of the fall character of a number of samples indicated that distinct upper and lower boundaries were present in the falling samples, and those boundaries remained coherent over the entire range of observation. The populations of the boundaries, once established, seemed to remain relatively constant, and with minor exceptions there appeared to be no interchanging of spheres contributing to the boundaries. Figure 3 shows a sketch of typical boundary conditions, and as indicated the convention of "nose" and "tail" designations for the faster and slower falling boundaries is adopted for use in further discussion. The motions of the particles within each group were extremely complex and these motions included the boundary spheres. Except when a few particles fell entirely independently of the groups, the motions of the majority of the spheres were very erratic: the spheres did not fall straight towards the bottom of the tube, but they moved in a turbulent, interrelated system on which collision with the wall seemed to play some important role in defining the types of particular motions. The turbulent motions were intensified in the heavier samples, but turbulence was present in all of the samples.

The boundary fall times represent the maximum and minimum fall times for the great majority of the spheres present in each sample. The fall times of the boundaries of each quantity of sample were measured a minimum of five times over distances of either 100 cm (coarser samples) or 50 cm (finer samples). Spot checks were frequently made by timing a given boundary over the upper half of the measured range, and then over the lower half. There were good agreements between such fall times, and in general fall times were found to be very consistent.

FALL VELOCITIES

The fall velocities of the boundaries of the samples of glass spheres are shown in figure 4 and are listed in table 3.

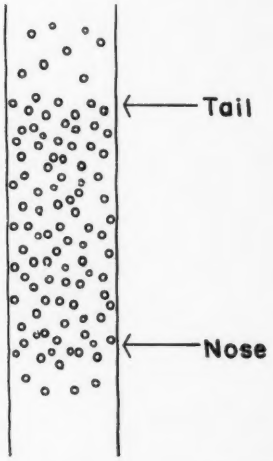


FIG. 3.—Sketch showing boundaries in falling sample.

TABLE 3.—*Boundary fall velocities in cm per sec of samples of glass spheres in water at 27 degrees centigrade*

Sample Med. (mm)		Sample Weight (gms)							
		0.25	0.50	0.75	1.0	2.0	3.0	4.0	5.0
0.784	Nose	13.21	13.22	13.33	13.35	13.47	13.70	13.47	13.48
	Tail	11.65	11.49	11.36	11.16	10.71	10.64	10.47	10.22
	Avg.	12.43	12.36	12.35	12.26	12.09	12.17	11.97	11.85
0.651	Nose	10.63	10.79	10.91	11.00	11.06	11.06	11.06	11.16
	Tail	9.59	9.24	8.98	8.91	8.65	8.74	8.77	8.77
	Avg.	10.11	10.02	9.95	9.96	9.86	9.90	9.92	9.97
0.548	Nose	9.07	9.09	9.09	9.14	9.24	9.26	9.26	9.28
	Tail	7.67	7.60	7.39	7.26	7.15	7.14	7.15	7.14
	Avg.	8.37	8.35	8.24	8.20	8.20	8.20	8.21	8.21
0.443	Nose	7.42	7.34	7.49	7.51	7.63	7.44	7.75	7.69
	Tail	6.11	5.94	5.74	5.83	5.83	5.96	5.85	5.73
	Avg.	6.77	6.64	6.62	6.67	6.73	6.70	6.80	6.71
0.383	Nose	6.34	6.35	6.28	6.30	6.34	6.33	6.34	6.35
	Tail	5.27	5.24	5.03	5.00	4.97	4.91	4.86	4.74
	Avg.	5.81	5.80	5.66	5.65	5.66	5.62	5.60	5.55
0.325	Nose	5.40	5.35	5.41	5.46	5.67	5.67	5.81	5.81
	Tail	4.10	4.03	4.06	4.11	4.04	3.95	3.92	3.88
	Avg.	4.75	4.69	4.74	4.79	4.86	4.81	4.87	4.83
0.274	Nose	4.21	4.36	4.29	4.39	4.50	4.56	4.63	4.66
	Tail	3.52	3.47	3.50	3.49	3.40	3.34	3.25	3.22
	Avg.	3.87	3.92	3.90	3.94	3.95	3.95	3.94	3.94
0.219	Nose	3.31	3.41	3.62	3.69	3.59	3.68	3.78	3.85
	Tail	2.52	2.52	2.39	2.36	2.31	2.29	2.27	2.26
	Avg.	2.92	2.97	3.01	3.03	2.95	2.99	3.03	3.06
0.187	Nose	2.88	3.00	3.10	3.12	3.18	3.35	3.44	3.50
	Tail	2.27	2.17	2.17	2.15	2.09	2.06	2.01	2.00
	Avg.	2.58	2.59	2.64	2.64	2.64	2.71	2.73	2.75
0.173	Nose	2.81	2.89	2.94	2.98	3.03	3.09	3.13	3.17
	Tail	1.82	1.79	1.72	1.65	1.62	1.61	1.59	1.56
	Avg.	2.31	2.34	2.33	2.31	2.33	2.35	2.36	2.37
0.136	Nose	2.48	2.57	2.60	2.64	2.70	2.74	2.76	—
	Tail	1.38	1.32	1.33	1.18	1.14	1.12	1.08	—
	Avg.	1.93	1.94	1.96	1.91	1.92	1.98	1.92	—
0.119	Nose	1.76	1.95	2.06	2.22	2.35	2.42	2.62	2.73
	Tail	1.03	0.98	0.97	0.96	0.95	0.93	0.90	0.89
	Avg.	1.40	1.47	1.52	1.59	1.65	1.68	1.76	1.81

Each of the weight-velocity curves in figure 4 appears to be unique, but the curves show two consistent trends: (1) the nose velocities tend to increase, and (2) the tail velocities tend to decrease with increasing sample weights. The greatest rates of change in velocity occur in the smaller weight intervals which generally extend from 0.25 to 1.0 gm. At greater weights, velocities appear to change uniformly with increasing sample weights. For each size grade, the rates of change in velocity for the nose and tail boundaries are different; for the same boundary in different samples, the rates of change are somewhat different. The nose and tail curves of the same sample do not

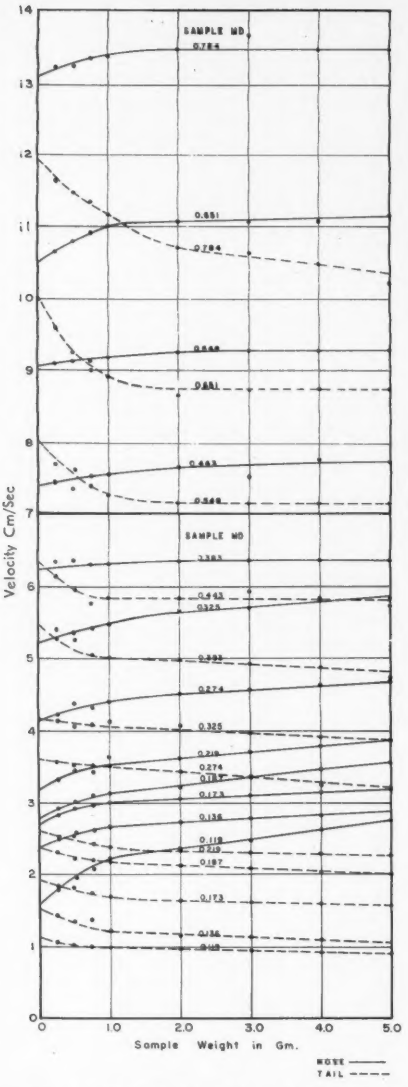


FIG. 4.—Fall velocities of boundaries of twelve size groups of spheres run in various concentrations. Solid line represents "nose," or leading boundary, and dashed line represents "tail," or trailing boundary.

intersect even when extrapolated to the zero weight axis.

Figure 5 is a graph of the averages of the boundary velocities of the samples. The figure shows that a general relationship exists between the size of the particles composing a sample and the settling velocity of the sample in water. The average velocity decreases with increasing quantity of sample for the coarser grain sizes, and the average velocity increases with increasing quantity of sample for the finer grain sizes. There appears to be no change in average velocity with sample weight for a sample having a median diameter of about 0.35 mm.

In figure 4, the differences between nose and tail velocities of the same sample increase with increasing weight. The actual differences taken at constant weight are greater for the coarser samples. The differences in velocity were grouped and averaged as shown in figure 6 in order to generalize the effect of size and weight on the differences. The groupings suggest that no simple correction factor could be determined which would account for changes in velocity with

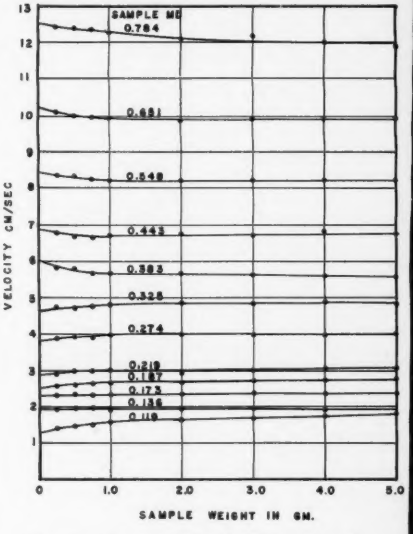


FIG. 5.—Average fall velocities of samples.

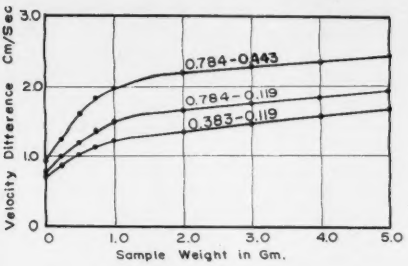


FIG. 6.—Average differences between sample boundary velocities.

changes in size or sample weight. With regard to sample weight, the average of all samples (0.784 to 0.119 mm) shows a difference of about 1.0 cm/sec at 0.25 gm, 1.48 cm/sec at 1.0 gm, and 1.92 cm/sec at 5.0 gm. The latter differences represent about 1½ and 2 times, respectively, the difference in velocity at 0.25 gm. The convergence of the grouped difference graphs towards a mean of about 1.00 cm/sec at 0.25 gm strongly suggests that extremely small quantities of the samples are required in order for the spheres to achieve velocities relatively independent of sample weight. For the experimental samples, that weight would have to be less than 0.25 gm.

The percentage changes in nose and tail velocities with sample weight are given in figure 7 in order to show the relative magnitude of the velocity variations with size. This figure shows the percentage net change in velocity at 1.0 and 5.0 gm relative to the graphic velocities at zero weight of the respective boundaries. It suffices for present purposes to consider the "zero weight velocity" as a common basis for comparison of the velocities at real weights; however, some meaning will be given to the zero weight velocities in a following section. Referring to figure 7, it can be seen that the percentage change in both nose and tail velocities increase with decreasing particle size. However, over the size interval of 0.784 mm to about 0.325 mm the percentage change seems relatively independent of particle size, but at smaller sizes the velocities change markedly with decreasing median diameter.

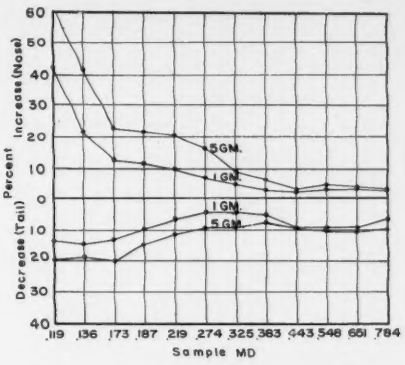


FIG. 7.—Percentage changes in boundary velocities relative to graphic zero-weight intercept velocities of the respective boundaries.

RELATION OF FALL VELOCITY TO PARTICLE DIAMETER

The foregoing discussion has considered the samples simply as groups of spheres while disregarding the size distribution within the groups. If densities may be assumed uniform, then it is entirely likely that physical size and sample sorting determine whether or not particles of a given diameter fall as nose spheres, tail spheres, or in an intermediate position somewhere within the sample boundaries. However, in different experimental samples which were gradational in size, there may have been sufficient numbers of spheres of a certain size to form (1) the nose boundary of a smaller median diameter sample and (2) the tail boundary of a larger median diameter sample. If size alone were the only factor involved in settling velocity, then a particle of a given size would fall at a characteristic velocity in either the coarser or the finer sample. This velocity would be the same as the single grain fall velocity in still water. Such still water velocities were not achieved in the experimental samples because the groups of falling spheres gave rise to turbulent conditions. As may be seen in figure 4, the nose spheres of a finer sample may have actually fallen faster than the tail spheres of a coarser sample. The difference in settling velocity of spheres of the same size falling among dif-

ferent groups of spheres is some measure of the effects of the fall systems on those spheres.

The boundary velocities of all the samples have been shown to change with sample weight, and in all quantities considered, various degrees of turbulence were observed. The apparent turbulent motions diminished with sample weight. It follows that in approaching the weight of only a few spheres the fall environment of the particles making up the sample would become essentially quiescent, and settling velocities would be those characteristic of the individual grains. Since the weight of the largest sphere used in this investigation was small when compared to the weight of the lightest sample (0.25 gm), the weights of the samples falling under quiescent conditions were much nearer to zero weight than they were to 0.25 gm. On this basis, the velocities of those spheres in quiet water can be determined by the extrapolation of the nose and tail curves to zero weight. While this tends to introduce small errors in velocities due to the different directions of slopes of the curves for the noses and tails, the boundary velocities at zero weight are assumed to be representative of the average boundary spheres under quiescent conditions of fall for purposes of the following discussion.

The boundaries of the samples were selected where a significant number of particles filled the cross section of the settling tube. It would be expected that a change in average size of the boundary spheres would result with a change in sample weight. That is, in a 0.25 gm sample, particles of the 95 percentile diameters may be so few in number that they would be incapable of forming a boundary which could be timed, while in a 5.0 gm sample great numbers of particles of the 95 percentile diameter would be present and they would contribute appreciably to the formation of the boundary. While this was probably the case to some extent, boundaries of all the samples were reasonably well defined, and the velocities as measured represented a good average for the leading and trailing spheres. Efforts were made to determine the average sizes of boundary spheres for different weights of each sample by withdrawing some of the leading and trailing spheres and measuring them optically. These measurements failed to reveal changes in average boundary sizes because mixing of the spheres occurred in the drawn-down portion of the settling tube. However, it was reasonably established that the average boundary sizes were generally of the order of the extreme 10 or 15 percentile diameters. Since the measurements were, at best, only approximations, the following reasoning was developed. If the sizes of the spheres assumed for the boundaries were actually representative, then those diameters with the quiescent velocities attributed them should define a common smooth curve comparable to independently determined fall data. Several trial graphs were prepared assuming diameters for the zero weight "velocities," and it was found that the best curve resulted when the nose velocities were attributed to the 90 percentile diameters and the tail velocities to the 10 percentile diameters. The resulting graph is shown in figure 8.

Before proceeding further, it is well to compare figure 8 with both theoretical and independently determined velocity-diameter relationships. These are shown in figure 9. The experimental curve, taken from Report No. 7 (1943, p. 18, fig. 1) shows the

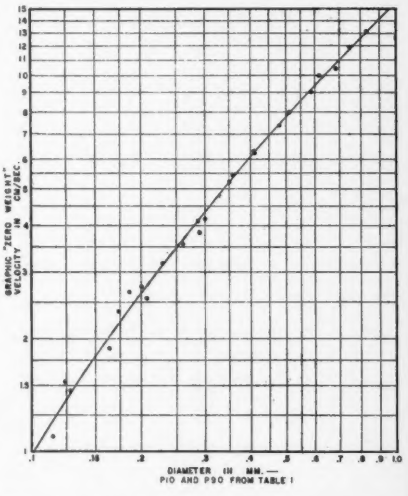


FIG. 8.—Graphic fall velocities for boundary spheres under quiescent conditions of fall.

velocities for quartz spheres in water at 30 degrees Centigrade. The curve lies fairly uniformly above the zero weight curve of the present study as would be anticipated from the higher specific gravity of quartz and the lower temperature used in this investigation. Stokes and Impact Law velocities were calculated from the familiar equations for standard conditions. The zero weight velocities are in reasonable agreement with the Stokes velocities over the smaller particle range, but they seem to have no apparent relationship to the Impact Law velocities. It is believed that the fall relations of the boundary spheres under quiescent conditions are approximately described in figure 8.

Since average boundary diameters may have shifted towards the extreme sizes present in the samples as weights were increased, it is difficult to determine what sizes of spheres are representative of the boundaries in practical weights of samples. Considering the frequency curves of the samples (fig. 1), small changes in the two extreme deciles of any sample would only result in very small changes in the diameters as taken for the zero weight velocities, with the maximum possible changes being governed by the size limits of the samples. Since the actual results were representative of the sizes present in the 10 and 90 percentile diameter fractions, it is likely that those sizes may be taken as the approximate average sizes of the boundary spheres of the heavier samples without introducing appreciable error. Figure 10 was prepared by attributing the nose and tail velocities at 1.0 and 5.0 gm to the 90 and 10 percentile diameters of the respective samples. The effects of attributing the velocities to different sizes may be seen from the figure. In relation to the diameters as taken, sizes nearer to the class limits of the samples would tend to decrease the velocity difference between nose and tail curves, taking the velocity along a diameter line. If sizes nearer to the median were used, the result would be a spreading of corresponding nose and tail curves. In either event, almost any reasonable sizes attributed to the boundary velocities would result in discrete nose and tail curves.

As may be seen in figure 10, the nose curves of the samples either lie very close to or well above the zero weight curve, while the tail curves lie below the zero weight curve. Remaining within both the physical

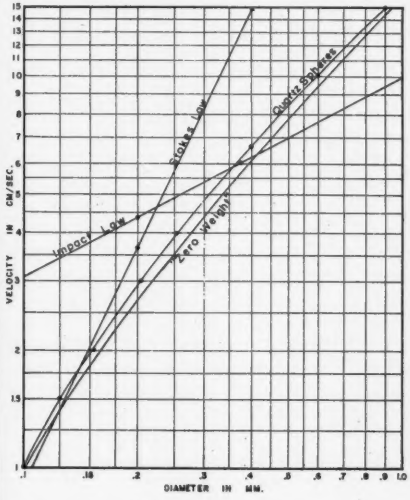


FIG. 9.—Relationships of single grain fall velocities to experimental and theoretical fall velocities.

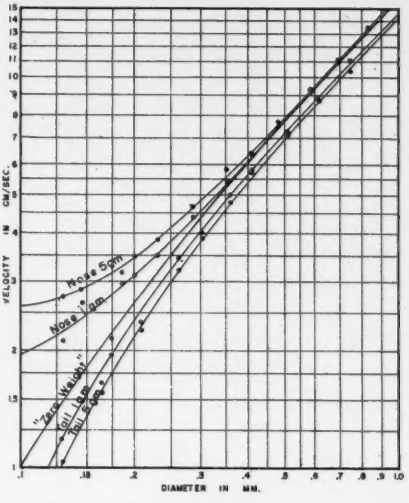
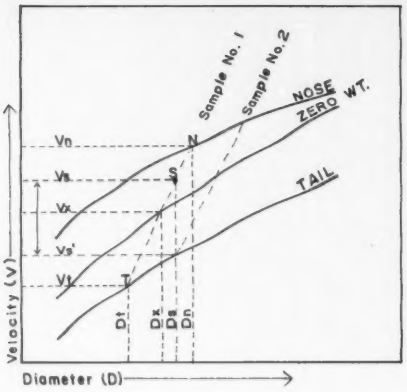


FIG. 10.—Turbulent fall velocities of boundary spheres.



subscripts:

n = nose, sample no. 1
t = tail, sample no. 1
x = spheres falling at laminar vel., sample no. 1
s = spheres having increase in vel., sample no. 1
s' = spheres having decrease in vel., sample no. 2

FIG. 11.—Enlarged sketch of portions of figure 10.

and geometric limits of the experimental samples, figure 10 represents a measure of the effects of group fall on the settling velocities of the boundary spheres. The nose velocity curve represents the maximum velocity a quantity of spheres of given size may achieve and the tail curve represents the minimum. Standard fall velocity has little meaning in terms of figure 10, for a given velocity may be attributed to any number of diameters if the particles fall as a group. For example, a velocity of 3.0 cm/sec is achieved by boundary spheres of the following sizes:

0.250 mm	tail, 5.0 gm sample
0.237 mm	tail, 1.0 gm sample
0.222 mm	"single sphere"
0.192 mm	nose, 1.0 gm sample
0.160 mm	nose, 5.0 gm sample

In the foregoing, size variations were calculated about the diameter of the "single sphere." Boundary spheres falling at 3.0 cm/sec may actually be 13 percent larger to 26 percent smaller than the size represented by the single sphere curve. This strongly suggests that the velocities in turbulent group fall are characteristic only of the relative sizes *in the samples* in which the velocities were determined.

If the variations in boundary velocities are correctly represented in figure 10, it seems safe to assume that the velocities of intermediate sized particles vary in some uniform manner between the limiting boundary velocities. The problems involved in establishing the fall velocities of the intermediate sizes can be illustrated by the enlarged sketch of the limiting relationships shown in figure 11. In figure 11, line TN represents entirely hypothetical variations in velocities of the various particles making up sample no. 1. The exact nature of TN is unknown, and presumably the *form* and *continuity* of the line are functions of sample weight, sorting, and physical size limits of the sample. Points T and N with their appropriate coordinates are, however, the limiting points of the line. From the relationships shown, diameter Dx represents the only size sphere which will fall at its quiescent, single grain velocity (Vx) in sample no. 1. The velocities of larger particles are increased and velocities of smaller particles are decreased. Suppose point S were established for a particle of diameter Ds. The velocity (Vs) would be appropriate for spheres of that diameter (Ds) only as long as spheres of that size enjoyed a relative position in the size distribution between Dx and Dn in sample no. 1. If the spheres of Ds were present in the coarser sample no. 2, they would be of proper size to form the tail boundary and fall at a velocity of Vs′. The velocity of spheres (Ds) would be decreased by the difference between Vs and Vs′.

The great problem in practical settling analyses of sand lies in determining just where an unknown sample fits into a scheme such as shown in figure 11. As presented, figure 11 depends upon the observed increases and decreases in settling velocity, but the rationale is valid as long as systematic changes in velocity occur. McNown and Lin (1952), working with uniformly sized spheres, have shown that similar changes in average group fall velocities occur and they were related to particle concentration. Others (Poole, 1957, p. 465–466, and Report No. 11, 1957, p. 34) have shown that apparently an increase in settling velocity of all size fractions took place in their sand samples. Their conclusions were based largely on deviations from known volumes in the particular size grades. The general in-

creases in velocity probably were due to both concentration effects and the range in size distributions of the samples. Smaller particles may be dragged down in the turbulent wake of the larger particles until those smaller particles are capable of breaking away to fall as groups of hydraulic equivalents appropriate to the system. Therefore, the fines may fall at several different velocities over the range of observation and average settling velocity based on accumulated volume may reflect a number of accelerations. These average velocities would presuppose the same influences and effects between the different grains and concentrations in every different sample, and it is questionable whether analytical results based on such velocities have meaning when extended to widely differing samples.

NATURE OF GROUP FALL

The nature of fall of the groups of experimental spheres was extremely complex and can only be described in general terms on the basis of available data. Particle movements within the groups seemed to be closely interrelated. The lower limit of group movement defined the noses of the samples and the tails were defined as the upper limit of the spheres having related motions. Included within the boundaries were essentially all of the particles making up a sample, and these particles followed their several ill-defined, but certainly not straight line, paths to the bottom of the tube. Report No. 12 (1957, p. 43) compares the settling of their samples to turbidity currents, and considers the current to be a result of unequal distribution of particles in the settling tube. In an experimental sample, the effect would be an increase in velocity of the coarser particles, setting up turbulent currents and eddies. Farther up in a turbulent sample, particle movement would become more restricted as concentration became more nearly equalized. Spheres in intermediate positions, as well as those forming the tail boundary of the group, would become more responsive to the buoyant effects of the eddies and currents. This would result in a measureable retardation of the finer particles present in the samples.

The experimental evidence suggests that only buoyant effects are realized in the fall of the coarser samples. In figure 7, as well as figure 10, the nose variations of samples coarser than 0.325 mm are small, averaging about 3 to 4 percent, while tail variations are consistently about 10 percent. For neither boundary does the variation differ greatly for either 1.0 or 5.0 gm samples. It appears that the coarser samples are to some extent incapable of turbid flowage in the settling tube employed, probably due in part to the large particle sizes. For the finer samples, some sort of turbid group movement is established in the noses of the samples which comes increasingly developed with decreasing size, with corresponding increases on the buoyant effects on the fines. None of the evidence definitely points toward dragging of the fines by the coarse particles within a sample (figures 7, 10) as would be expected from the small range in sizes present.

SUMMARY AND CONCLUSIONS

The samples used in this investigation were glass spheres having small ranges in size (0.25 phi unit) with sample median diameters ranging from 0.784 mm to 0.119 mm. Fall velocities were determined in an Emery type settling tube by measuring the minimum (nose) and maximum (tail) fall times of the samples over known distances. In all samples, the nose velocities increased and the tail velocities decreased with increasing sample weights. The average of the two velocities for samples coarser than about 0.35 mm (median diameter) decreased with increasing sample weight and the average velocities of finer samples increased with increasing sample weight. The greatest rates of change in the boundary velocities occurred in the low weight ranges from 0.25 gm to about 1.0 gm. Differences between the two boundary velocities for a given sample increased with sample weight, and in general the coraser samples showed greater differences between nose and tail velocities. The percentage changes in velocities relative to single grain fall velocities for appropriate sized spheres generally decreased with increasing particle size except for samples coarser than 0.325 mm. In the coarser samples, percentage change of both boundary velocities seemed to be relatively independent of the sample median. The nose and tail velocities were attributed to certain particle sizes in order to develop the

diameter-velocity relations for conditions of (1) single grain fall in quiescent water and (2) group fall in a turbulent system.

The experimental findings were viewed primarily from their relations to the problems of establishing standard fall velocities for use in settling analyses of sands. The settling of almost any practical quantity of the samples gave rise to a turbulent fall system in which particle concentration and size were shown to be related to the magnitude of the resulting velocity changes. It is believed that turbulent effects are realized in any settling analyses of sands in which accumulated volumes cannot be directly related to single grain velocities. While corrections can be made for shape and roughness of grains, there is no assurance that a majority of the grains in a sample will fall at characteristic velocities in a congested system. Grains falling in a turbulent system do not achieve terminal, uniform settling velocities which are always characteristic of the grain dimensions; rather they achieve fall velocities characteristic only of the particular system in which they fall. Such systems cannot be expected to be reproducible from one sand to another, and it is believed that the concepts of standard fall velocity and sedimentation radius have little meaning in those turbulent systems. This is shown most clearly in figures 10 and 11, and very similar velocity changes are likely in sands having approximately the same size ranges and geometry. Sands having wider ranges in size, which would include most sands, would seem to be represented by portions of the line TN in figure 11 lying above the zero weight curve. This means that even if turbulent fall velocities were utilized, each sample to be analyzed must be fitted into a scheme where possible changes in velocity may be either in one direction (general increase of Report No. 11, 1957), or two directions as in the experimental samples. Substantial errors in analyses under such turbulent conditions seem inherent in the system.

The problem seems to be one of establishing proper test dimensions so that the concept of sedimentation radius can be given some practical meaning in relation to settling of sands. Two courses of action seem fruitful. First, the cross sectional area of the settling tube should be reconciled in terms of quantity of sample used, in order to permit grains to fall independently. In this regard, it would appear that the apparatus of Zeigler, Whitney, and Hayes (1960) has considerable merit in using a large bore settling tube. A second technique would rely on the fact that at least rates of accumulation of sediments in a given sample are reproducible (Poole, Butcher, and Fisher, 1951), regardless of how the rates of accumulation may be related to single grain velocities. Quartz calibration spheres could then be included in the samples, and measurements of the intervening volumes between calibration spheres of different sizes could be made. If the grains fell freely, true sedimentation radii would be obtained.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 1, PP. 113–122
FIG. 1, MARCH, 1961

ANALYSIS OF CARBONATE ROCKS FOR CALCIUM, MAGNESIUM, IRON, AND ALUMINUM WITH EDTA[1]

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ABSTRACT

A procedure for the rapid volumetric analysis of carbonate rocks for calcium, magnesium, iron, and aluminum is presented in a form to aid the inexperienced analyst. The four elements are determined with the use of EDTA (ethylenediaminetetracetic acid), an organic chelating agent. Instructions for the gravimetric determination of silica are also included.

Literature concerning the determination of calcium, magnesium, and iron with EDTA has appeared in the chemical journals (Cheng and others, 1952; Banewicz and Kenner, 1952; see also Welcher, 1958), and the adaptation of EDTA techniques to the determination of aluminum has also been discussed (Wanninen and Ringbom, 1955; Davis and Jacobsen, 1960). The inexperienced analyst might find it difficult, however, to trace and apply the information to the problem of analyzing carbonate rocks for the four elements mentioned. It is felt that this report will enable a person with a minimum of analytical training to perform analyses rapidly and with accuracy sufficient for most commercial and investigative needs. A list of the chemicals and equipment required is included, and sample calculations are given. Knowledge of only the most fundamental laboratory operations such as "dilute to volume," "titrate," "transfer quantitatively," and "pipette," is assumed.

GENERAL INFORMATION

The amount of a standard solution of EDTA necessary to react with a given metal ion may be directly measured by adding the EDTA solution to a solution of the metal under conditions such that the end point of the reaction may be detected. In this case, visual indicators are used to produce a color change which marks the point of complete reaction. Since calcium and magnesium react quantitatively with EDTA under the same conditions and a suitable indicator is available, it is a simple matter to titrate the sum of calcium and magnesium in a sample aliquot. By titrating another aliquot of the same sample at a higher pH, it is possible to determine calcium only, the magnesium having been rendered "unreactive" at this higher pH level. Hence, the amount of magnesium may be calculated by considering the difference between the two determinations.

Ferric iron reacts rapidly and quantitatively with EDTA in the low pH range at room temperature, while aluminum under these conditions reacts very slowly—so slowly, in fact, that iron can be titrated directly even in the presence of aluminum provided that the solution is not heated. By raising the temperature to boiling, the very slow aluminum reaction may be "pushed" to completion. Hence, the sum of aluminum and iron in an aliquot may be determined by adding a measured excess of EDTA, boiling to insure complete reaction of both ions, and then determining the amount of EDTA "left over." This latter determination is accomplished by a titration of the excess EDTA with a zinc solution after addition of acetone and adjustment of pH. Dithizone is used as a visual indicator. The amount of iron and aluminum present is then calculated from the difference in the amounts of EDTA originally added and the amount found in excess after causing all of the iron and aluminum to react.

Iron is then determined in another aliquot by way of a simple direct titration, and the amount of aluminum is calculated by difference. The complete scheme is represented diagramatically in figure 1. (See also "calculations")

DISCUSSION

Carbonate rocks are composed essentially of the minerals calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). These minerals are readily soluble in hydrochloric acid while most of the common foreign materials found in carbonate rocks are not. Among these foreign

[1] Ethylenediaminetetracetic acid; Manuscript received April 11, 1960.

LIST OF NECESSARY EQUIPMENT AND CHEMICALS

Equipment

1. Analytical balance (± 0.1 milligram)
2. Beakers; 400 ml, 600 ml
3. Burettes; 50 ml and 10 ml
4. Crucibles; platinum or porcelain
5. Desiccator
6. Erlenmeyer flasks; 300 ml
7. Electric hot plate
8. Filtering crucibles (optional, see "Discussion")
9. Filter paper; Whatman No. 42
10. Funnels, narrow-stem glass
11. Meker burner
12. pH meter (±0.1 unit)
13. Pipettes; 5 ml, 10 ml, 25 ml, 50 ml
14. Reagent bottles; several 500 ml, several 50 ml (dropper type) three large storage type
15. Stirrer, magnetic type (optional, but desirable for titrations in Procedure III)
16. Volumetric flasks; 500 ml, 1 liter

Chemicals

1. acetone
2. aluminum metal, standard-pure
3. ammonium chloride
4. ammonium hydroxide
5. ammonium persulfate
6. calcium carbonate, reagent grade
7. disodium salt of EDTA ("Versene," "Hachver," etc.)
8. dithizone (diphenylthiocarbazone) Eastman Kodak
9. eriochrome black T (F241) Eastman Kodak
10. Ethyl alcohol
11. hydrochloric acid
12. hydroxylamine hydrochloride
13. iron metal, standard-pure
14. magnesium chloride hexahydrate
15. murexide (ammonium purpurate) Eastman Kodak; or "Calver II," Hach Chemical Company
16. potassium cyanide
17. potassium hydroxide
18. salicylic acid
19. sodium acetate
20. sodium carbonate
21. sodium hydroxide
22. sodium tartrate
23. zinc metal, standard-pure, or reagent grade zinc acetate ($Zn(C_2H_3O_2)\cdot 2H_2O$)

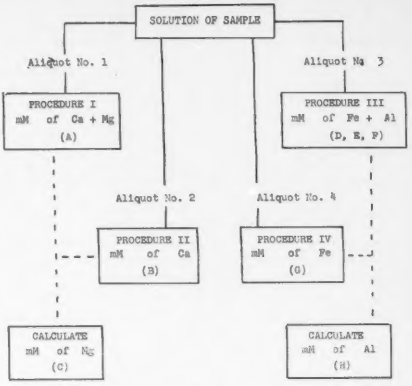

FIG. 1.—Outline of analysis.

materials are chert (dominantly SiO_2), clay minerals (variable in composition, but rich in silica and alumina), quartz (crystalline SiO_2), and quite commonly pyrite (FeS_2).

When a carbonate rock sample is powdered and dissolved in hydrochloric acid, the carbonate minerals pass readily into solution while practically all of the non-carbonate material is insoluble. If this "insoluble residue" is removed by filtering or allowed to settle out, the solution contains: (1) calcium and magnesium derived from the carbonate minerals; (2) minor amounts of other elements such as iron and manganese which may have been incorporated in the carbonate minerals; and, (3) additional elements which may have been leached from essentially insoluble foreign substances such as chert or clay. In other words, some silica may be in solution because of the presence of finely divided chert, or clay particles may have yielded some aluminum and iron. Once these elements are in solution, there is no way to differentiate, for instance, between iron which may have been present in the readily soluble dolomite and iron which may have been leached from clay particles.

It is proper to refer to the substances which remain out of solution as the "acid insoluble residue" and to refer to the solution as the "hydrochloric acid extract" of the sample. The concentration of the acid used and the time and temperature of solution should be mentioned when reporting such results. The author tentatively suggests one-half hour in 150 ml of 3N hydrochloric acid at 50°–60° C as a suitable set of conditions for powdered samples of approximately 1 gm. It is felt that this treatment insures solution of all of the carbonate minerals and is not intense enough to attack most clay minerals to any appreciable de-

CALCULATIONS

A = mM of Ca+Mg = ml used to titrate aliquot No. 1, multiplied by 0.025

B = mM of Ca = ml used to titrate aliquot No. 2, multiplied by 0.025

C = mM of Mg = $A - B$

D = mM of EDTA added to react with Fe+Al (procedure III) = ml of EDTA solution added, multiplied by 0.005

E = mM of EDTA in excess (procedure III) = ml of zinc solution used, multiplied by 0.001

F = mM Fe+Al in aliquot No. 3 = $D - E$

G = mM of Fe in aliquot No. 3 = ml of EDTA used to titrate aliquot No. 4, multiplied by 0.005 and multiplied by a factor equal to:

$$\frac{\text{ml in aliquot No. 3}}{\text{ml in aliquot No. 4}}$$

H = mM of Al = $F - G$

$$\% \ CaCO_3 = B \times 100.0$$

$$\% \ CaO = B \times 56.0$$

$$\% \ MgCO_3 = C \times 84.3$$

$$\% \ MgO = C \times 40.3$$

$$Ca/Mg \text{ mole ratio} = B/C$$

$$\% \ Ca, Mg(CO_3)_2 = C \times 184.4$$

$$\% \ FeO = \frac{G \times 7.2}{X}$$

X = 0.05 if aliquot No. 4 was 50 ml
= 0.10 if aliquot No. 4 was 100 ml
etc.

$$\% \ Al_2O_3 = \frac{H \times 5.1}{Y}$$

Y = 0.01 if aliquot No. 3 was 10 ml
= 0.02 if aliquot No. 3 was 20 ml
etc.

$$\% \ SiO_2 = \text{wt. of } SiO_2 \text{ in gm} \times 100$$

% "acid insoluble residue" via Procedure 2 = wt. of residue in gm × 100
% "acid insoluble residue" via Procedure 3 = wt. of residue in gm × 10

gree (Grim, 1953). If investigators would adhere to some such set of conditions as a standard, more meaningful comparison of results might be made.

The other, and most common, method of putting carbonate rock samples into solution involves a fusion of the samples prior to treatment with hydrochloric acid. This procedure results in a solution containing all of the elements found in the rock. SiO_2 is then

precipitated and removed by filtration to be dried and weighed. This is the type of treatment normally assumed when a percentage value for SiO_2 is reported. In this case the aluminum and iron in chert or clay particles has been rendered soluble and can be determined by procedures such as those outlined in this report.

In considering rapid methods involving EDTA for the proximate analysis of marl samples, Goldich and others (1959) discuss the problem of reporting results for insoluble material. They point out that the marl samples contain small amounts of silicates such as microcline, plagioclase, epidote, and hornblende, which are not readily broken down into their component elements by standard fusion procedures. Although their method calls for a fusion of the sample, they report a value for the "insoluble" (insoluble residue) rather than for SiO_2. Their insoluble residue, therefore, is essentially SiO_2 with minor amounts of silicate minerals which resist breakdown during fusion.

These minerals, however, are exceedingly rare in most marine carbonate rocks, and a fusion suffices to break down the more common clay minerals and prepare the sample for the determination of SiO_2 (Diehl and Smith, 1955 p. 436–438). The case of the marl analysis report by Goldich and others demonstrates the desirability of an understanding of the mineralogical makeup of a rock sample in reporting the results of a chemical analysis. In this case, the awareness of the authors has prevented confusion.

The magnesium content of a rock is usually reported as the oxide MgO. In carbonate rock analyses it may be reported as percent $MgCO_3$ or percent Ca $Mg(CO_3)_2$ (dolomite). In either of the latter cases it should be made clear as to whether the reported results actually indicate the presence of the mineral. For example, if X-ray investigation shows that a magnesium-bearing carbonate rock contains no magnesite and the presence of dolomite is indicated, an investigator may assume that most of the magnesium found was incorporated in dolomite and report it as such. For a discussion of equilibria involving the magnesium-bearing phases of carbonate rocks the reader is referred to Fairbridge (1957).

When proper identification of mineral constituents has *not* been made, it would be improper, for example, to report a "percent dolomite" based on magnesium determinations without qualifying the notation. Reporting a "maximum possible Ca $Mg(CO_3)_2$ content" would be permissible. Use of the *word* "dolomite" in the latter statement might introduce some ambiguity because of the existence of iron-bearing (ankeritic) dolomites.

SAMPLE TREATMENT

Procedures for the determination of the "acid insoluble residue" and for the determination of SiO_2 are outlined below. In each case, the resultant solution is suitable for the analysis for calcium, magnesium, iron, and aluminum by the methods subsequently outlined.

Place a few gm of a representative powdered portion of the rock sample in a suitable open container and dry at 110° C for one hour. Allow the sample to cool to room temperature in a desiccator.

If it is desired to determine the amount of acid insoluble material and analyze the hydrochloric acid "extract," the rock samples should be treated as follows:

Procedure.—Place 1.00 gm of the properly prepared sample in a 400 ml beaker, slowly add 150 ml of 3*N* HCl (1 part HCl to 3 parts water) and hold the solution at 50°–60° C for one-half hour. If the amount of insoluble material is negligible or very small, it may be ignored and the solution transferred directly to a 1000 ml volumetric flask, cooled and diluted to volume. After allowing the residue to settle, the solution is ready to be analyzed via the procedures outlined.

If the amount of insoluble material is appreciable, it may be treated in one of three ways:

Procedure 1.—The solution may be filtered through a piece of analytical filter paper mounted in a glass funnel and the filtrate collected in a 1000 ml volumetric flask. The solids should be washed several times with dilute HCl (1:50) and the wash water collected along with the filtrate. Allow the solution to cool, and dilute to volume. After thorough mixing, this solution is ready to be analyzed by the procedures outlined. In this case, the percent of insoluble residue may be approximated by difference after the other major constituents have been determined in the extract.

Procedure 2.—If it is desired to determine the exact weight of the insoluble residue, it may be collected in a medium sintered glass filtering crucible fitted into a vacuum flask with a rubber adapter. This procedure is slower, requiring a weighing of the filtering crucible before and after filtration and at least 30 minutes of drying at 110° C before each weighing. The suction produced by a faucet-type aspirator is suitable for filtering the residue from even very argillaceous rocks if most of the filtrate is allowed to pass through the glass before the residue is washed onto it. The filtrate and washings must be quantitatively transferred into a volumetric flask before dilution as in "1" above.

Procedure 3.—If enough powdered sample is available, the amount of acid insoluble material may be determined more rapidly as follows· Treat 10.00 gm of the sample in 300–400 ml of approximately 6 N HCl (1:1) at room temperature for 30 minutes and separate the solids by filtering through a suitable filter paper. Dry the paper and residue at 100° C for an hour and weigh. Subtract from this weight the average weight of the same type filter paper after soaking and drying. A large sample (10.0 gm) is used to compensate for the error introduced by variations in filter paper weight; that is, the relative error is decreased. The filter paper weights usually do not vary more than 0.025 gm.

Because of the increased acid strength, more "leaching" of siliceous components may occur, but the amount will not be significant in determining the percent insoluble residue in this way. It may, however, be significant in determining the amount of aluminum or iron in the filtrate; hence the filtrate from this procedure should not be used for the determination of soluble components.

If it is desired to break the insoluble residue down into its component elements and analyze the sample for SiO_2, the following procedure should be used.

Procedure.—Place 1.00 gm of the properly-prepared rock sample in a platinum crucible and mix it intimately with 2 gms of sodium carbonate (Na_2CO_3). Porcelain crucibles may be used if platinum are not available. Heat the crucible gradually to a red heat to decompose the carbonate minerals by driving off CO_2. If the heating is too rapid, some of the solid may be lost. Then, heat at the full heat of a Meker burner for 30 minutes, keeping the platinum crucible above the tips of the blue cones of the flame. A muffle furnace may be used if available, heating the sample to 850°–900° C. Cool the crucible and place it in a 400 ml beaker. Cover the beaker with a coverglass and add 15 ml of water and 15 ml of concentrated HCl in alternate 5 ml portions. Wash down the coverglass and dilute the solution to 50–60 ml. After the solid has been separated from the crucible, remove the crucible with a hooked glass rod, being careful to rinse it thoroughly with a stream of wash water.

Evaporate the solution to dryness on a hotplate and heat until the residue and coverglass are completely dry. Add 5 ml of concentrated HCl and then 25 ml of water. Replace the cover and warm for 2 to 3 minutes, swirling the solution slightly. Dilute to approximately 100 ml and filter, using a hard, ashless filter paper (Whatman No. 42). Wash the SiO_2 with warm dilute HCl (1:50) until the yellow ferric iron has left the paper, and then wash twice with 5 ml of water. Transfer the filtrate and wash solutions to a 1000 ml volumetric flask. Cool and dilute to volume.

In order to weigh the SiO_2, it is necessary to burn away the filter paper. Carefully fold the damp paper containing the precipitate and pack it into the bottom of a crucible which has been previously ignited in a Meker burner for 20 minutes, cooled and weighed. Heat the crucible for several minutes by positioning it above the Meker burner, and slowly lower it to cause the paper to char completely without bursting into flame. When the paper is reduced to a black ash, ignite the crucible at the full heat of the burner for 20 to 30 minutes. Cool the crucible and silica in a desiccator and weigh. Determine the weight of SiO_2 by subtracting the weight of the empty crucible.

Details of the techniques used in determining SiO_2 gravimetrically can be found in most elementary quantitative analysis books.

PREPARATION OF REAGENTS

Standard Calcium Solution

Preparation.—Weigh exactly 2.500 gm of reagent grade calcium carbonate, which has been dried for 1 hour at 100° C and allowed to cool, into a weighing pan, and transfer the solid quantitatively into a one liter volumetric flask. Add dilute hydrochloric acid to completely dissolve the solid and dilute to

volume with distilled water at room temperature.

After thorough mixing, this solution is 0.025 M in calcium and will be used to standardize the EDTA solution.

Standard EDTA Solutions

EDTA Solution 1

Preparation.—Weigh 11.0 gm of the disodium salt of EDTA (M.W. 372.25) for each liter of stock solution desired into a beaker, and transfer the solid into a storage bottle of suitable size. Add 0.10 gm of magnesium chloride hexahydrate for each liter of solution, dilute to the approximate proper volume, and agitate to dissolve all of the solids. Each liter of solution will suffice for the analysis of at least 20 carbonate rock samples.

Titrate a 25 ml aliquot (delivered with a pipette) of the standard calcium solution with this EDTA solution as outlined under "Procedure I." Adjust the strength of the EDTA stock solution by diluting with water or, if necessary, by adding more EDTA, until 25.0 ml of the solution are required to titrate the 25.0 ml aliquot of standard calcium solution to the blue end point. The EDTA stock solution is then 0.025 M and suitable for the determination of calcium and magnesium as outlined.

EDTA Solution 2

Preparation.—A more dilute solution of EDTA must be prepared for use in the determination of iron and aluminum by Procedure III. This is done as follows: dissolve 9.4 gms of the disodium salt of EDTA in distilled water and dilute the solution to volume in a 1000 ml volumetric flask. Mix well and standardize the solution by titrating 25 ml aliquots of the standard calcium solution by Procedure I. Adjust the strength of the EDTA solution by adding distilled water until 25.0 ml are required to titrate the 25 ml aliquot of the standard calcium solution. The solution is then 0.025 M in EDTA but does not contain magnesium as does EDTA solution 1.

This stock solution will be diluted 1:5 to yield a 0.005 M solution to be used in Procedure III. The dilution must be made as accurately as possible by delivering an aliquot of the stock solution with a clean pipette into a volumetric flask and diluting to volume with distilled water at room temperature. Example: Pipette 100 ml of the 0.025 M EDTA solution 2 into a 500 ml volumetric flask, dilute to volume, and mix thoroughly.

The same stock solution (EDTA solution 2) is diluted 1:10 to yield a 0.0025 M solution which will be used to titrate iron by Procedure IV. Bottles used to contain this dilute solution should first be washed with a hot EDTA solution to which several pellets of sodium hydroxide have been added, and then rinsed thorougly with distilled water and finally rinsed with portions of the 1:10 solution.

Buffer solution for the titration of calcium plus magnesium or either in the absence of the other—Procedure I

Preparation.—Dissolve 68 gm of ammonium chloride and add 570 ml of concentrated ammonium hydroxide per liter of solution. Dilute to volume with distilled water.

Solution to adjust pH for titrating calcium in the presence of magnesium—Procedure II

Preparation.—Dissolve 450 gm of potassium hydroxide per liter of solution.

Potassium Cyanide Solution

Preparation.—Dissolve 2.5 gm of potassium cyanide per 100 ml of solution.

Caution: Potassium cyanide is a deadly poison if taken orally.

Caution: If any solution of potassium cyanide is acidified, deadly hydrocyanic acid is evolved.

This solution should be prepared fresh every few days. Alternately, 0.25 gms of solid potassium cyanide may be added before each titration.

Indicator for the titration of calcium plus magnesium via Procedure I

Preparation.—Place approximately 150 gm of sodium chloride in a mortar and add 0.5 gm of Eriochrome Black T (F241). Grind the solids with a pestle until the mixture is homogeneous. A small pinch, less

than the size of a pea, is used in the titration described in Procedure I.

Lindstrom and Diehl (1960) have reported using a new indicator, "Calagite, "(1-(1-hydroxy-4-methyl-2-phenylazo)-2-naphthol-4 sulfonic acid) for the titration of calcium plus magnesium and suggest that it has advantages over F241.

Indicator for the titration of calcium in the presence of magnesium by Procedure II

Preparation.—Place approximately 150 gm of sodium chloride in a mortar and add 0.5 gm of murexide, the ammonium salt of purpuric acid. Grind the solids with a pestle until the mixture is homogeneous. A pinch of this solid mixture is used in the titration described in Procedure II. Alternately, use the solid indicator mix "Calver II," sold by the Hach Chemical Company of Ames, Iowa.

Salicylic acid indicator solution for iron determination

Preparation.—Dissolve 2.0 gm of salicylic acid in 100 ml of ethanol.

Dithizone indicator solution

Preparation.—Prepare a saturated solution of dithizone in ethanol.

Sodium acetate solution

Preparation.—Dissolve 35 gm of reagent grade sodium acetate per 100 ml of solution. It may be necessary to dilute this solution for use in Step 2 of Procedure III.

Hydroxylamine hydrochloride solution

Preparation.—Dissolve 10 gms of hydroxylamine hydrochloride per 100 ml of solution.

0.001 M zinc solution

Preparation.—Dissolve 0.6538 gm of standard-pure zinc metal in a minimum amount of hot hydrochloric acid (1:1), cool the solution and transfer to a one liter volumetric flask. Dilute to volume and mix thoroughly. Portions of this solution must then be diluted 1:10 to prepare the 0.001 M solution used in Procedure III.

If standard-pure zinc metal is not available, dry approximately 5 gms of reagent grade zinc acetate dihydrate at 100° C for 1 hour and cool in a desiccator. Dissolve 2.195 gms of the compound in water and dilute to one liter. After thorough mixing, portions of this solution must be diluted 1:10 to prepare the 0.001 M solution used in Procedure III.

Standard solutions of iron and aluminum may be prepared and used to check results of Procedures III and IV. For example, if 10 ml of the 0.005 M EDTA solution is used, and 10 ml of a 0.001 M iron solution plus 10 ml of a 0.001 M aluminum solution are added, the following equations hold:

$$(\text{mM of EDTA added}) - (\text{mM of Fe}+\text{Al}) = \text{mM of excess EDTA}^2$$

$$(10\text{ ml}\times 0.005\text{ M}) - (10\text{ ml}\times 0.001\text{ M} + 10\text{ ml}\times 0.001\text{ M}) = 0.03\text{ mM}$$

and the excess 0.03 mM of EDTA should require 30.0 ml of the 0.001 M zinc solution in the titration.

$$\text{mM of excess EDTA} = \text{mM zinc}$$

$$0.03 = x\text{ml}\times 0.001\text{ M}$$

$$x = 30.0\text{ ml}$$

0.001 M iron solution

Preparation.—Dissolve 0.5585 gms of standard-pure iron metal in minimum amount of hot hydrochloric acid (1:1), cool the solution, transfer to a one liter volumetric flask and dilute to volume. This stock solution must then be diluted 1:10 to prepare a standard 0.001 solution.

If low results are found in checking Procedure IV with this solution, it may be necessary to add a few crystals of ammonium persulfate ($(NH_4)_2S_2O_8$) to the iron solution before titrating to insure that all of the iron is in the ferric form.

0.001 M aluminum solution

Preparation.—Dissolve 0.2697 gms of standard-pure aluminum metal in a minimum amount of hot hydrochloric acid (1:1), cool the solution, transfer to a one liter volumetric flask and dilute to volume. This stock solution must then be diluted 1:10 to prepare a standard 0.001 M solution.

[2] mM = millimole, one thousandth part of a mole, number of millimoles found by multiplying ml of solution by the molarity as shown in the above example.

PROCEDURES FOR DETERMINATION OF Ca, Mg, Fe, AND Al

Procedure I.—Determination of the Sum of Calcium and Magnesium or Either in the Absence of the Other

Place a 100 ml aliquot of the solution containing calcium and/or magnesium in a 300 ml erlenmeyer flask, or 400 ml beaker if a magnetic stirrer is used. Add 15 ml of the ammonium-ammonium-chloride buffer solution. Then add 5 ml of the 10 percent hydroxylamine hydrochloride solution, 10 ml of the potassium cyanide solution, several crystals of sodium tartrate and a small pinch of the F241 indicator. Mix thoroughly and titrate with the 0.025 M stock solution of EDTA. The end point is a change from a wine-red to a blue color which does not fade. If a poor end point results, increase the amount of buffer and/or decrease the amount of indicator added. In titrating solutions of impure carbonate rocks, the color after the end point may not be a pure blue.

The number of ml required for this titration multiplied by 0.025 gives the number of millimoles (mM) of calcium plus magnesium in the aliquot. See Figure 1.

Procedure II.—Determination of Calcium in the Presence of Magnesium

Place a 100 ml aliquot of the solution containing calcium and magnesium in a 300 ml erlenmeyer flask. Add 8 to 10 ml of the potassium hydroxide solution, 5 ml of the hydroxyl-amine hydrochloride solution, and 10 ml of the potassium cyanide solution. Then add several crystals of sodium tartrate, a "pinch" (approximately 0.1 gm) of the murexide indicator mixture or of "Calver II," and mix thoroughly to produce a pink solution. The solution may be cloudy at this point. Titrate with the 0.025 M stock solution of EDTA to a blue color. In titrating solutions of impure carbonate rocks, the color after the end point may not be a pure blue. The end point should not be approached too rapidly. If a poor end point results, increase the amount of potassium hydroxide solution added and/or vary the amount of indicator.

The number of ml required for this titration multiplied by 0.025 gives the number of millimoles of calcium in the aliquot.

Procedure III.—Determination of the Sum of Iron and Aluminum

Step 1.—The iron and aluminum in an aliquot of the sample solution must be caused to react with a measured amount of EDTA. The amount of excess EDTA must then be determined.

The sample aliquot size (aliquot No. 3) and the ml of EDTA solution necessary should be determined as follows:

Place an aliquot of the sample solution in a beaker. The appropriate aliquot size will range from 10 to 25 ml, depending upon the amount of foreign material in the rock. Pipette 10.0 ml of the 0.005 M EDTA solution into the beaker, add water to give a total volume of about 50 ml, boil gently for 1–2 minutes, and dilute with 40–50 ml of warm acetone (CAUTION). Adjust the pH of the hot solution to 4.3 to 4.4 with warm sodium acetate solution (using the proper temperature setting or correction) add 10 ml of the 0.001 M zinc solution and 10–20 drops of the dithizone indicator solution. If the resulting solution is pink, either the sample aliquot size must be reduced or more EDTA solution must be added. If the resulting solution is blue, an excess of EDTA is present and may be determined as outlined below in Step 2, taking into account the fact that 10 ml of the zinc solution have already been added. In analyzing rocks which are related geologically (for example, from the same formation), it is frequently possible to estimate the necessary ratio of sample aliquot size to volume of EDTA by judgement based on prior analyses of rocks from the same section. In a recent study, the ratio was estimated according to the previously determined calcium-magnesium ratios, or the amount of acid-insoluble material in the rock (Bisque and Lemish, 1959).

Step 2.—Mix appropriate amounts of the sample solution and the 0.005 M EDTA solution in a 600 ml beaker, add water to give a total volume of about 50 ml, adjust to pH 1–3, and boil for 1 to 2 minutes. Dilute with 40 to 50 ml of warm acetone (CAUTION) and adjust the pH of the hot solution to 4.3 to 4.4 with warm sodium acetate solution. Add enough dithizone indicator to give the solution a light blue color, and titrate with 0.001 M zinc solution keeping

the pH in the range 4.3 to 4.4 by adding sodium acetate solution drop by drop. The end point is a change to the pink color of the zinc-dithizone complex.

The number of ml of zinc solution used in this back-titration multiplied by 0.001 gives the number of millimoles of excess EDTA. This value subtracted from the number of millimoles of EDTA which were originally added gives the number of millimoles of iron and aluminum present in the aliquot. See Figure 1 and "calculations."

Procedure IV.—Determination of Iron

Place a 50 ml aliquot of the sample solution in a beaker and adjust the pH to 3.5 to 3.8 with the sodium acetate solution. Add 1 ml of the salicylic acid indicator, mix, and titrate with the 0.0025 M EDTA solution (prepared by diluting EDTA Solution 2) until all of the purple color has disappeared and the solution is light yellow or colorless. The pH should be monitored during the titration. If a sample contains a high percentage of iron, the solution may turn brown after the end point. This does not affect the results. In analyzing high iron samples (greater than one percent FeO), it may be necessary to use a 0.025 M EDTA solution. This must, of course, be taken into account in the calculation.

It is advisable to use a 10 ml burette graduated to 0.02 ml. for the iron titrations if small amounts of titrant are involved. A 100 ml aliquot of the sample solution may be used if the iron concentration is very low.

The number of ml of EDTA solution used in this titration multiplied by 0.0025 gives the number of millimoles of iron in the aliquot used. By calculating how many millimoles of iron this would represent in aliquot No. 3 and subtracting this value from the number of millimoles of iron plus aluminum previously determined, the number of millimoles of aluminum in aliquot No. 3 is found.

Results of 16 analyses of mixtures by three different operators are shown in Table 1.

INTERFERING ELEMENTS

The interfering ions which may be encountered in the titration of calcium and magnesium are, iron, copper, aluminum, manganese, cobalt, nickel, and zinc. The addition of cyanide serves to complex copper, cobalt, nickel, and zinc ions to prevent them from reacting with EDTA. Iron and manganese are reduced to their lower valence states by hydroxylamine hydrochloride and thereby prevented from interfering. Aluminum must be complexed by the addition of sodium tartrate.

TABLE 1.—*Results of aluminum determinations on mixtures*

Elements Present (millimoles)			Al Added (mM)	Al Found (mM)	Relative Error (%)
Ca (mM)	Mg (mM)	Fe (mM)			
3	3	0.0050	0.0100	0.0100[a]	0
3	3	0.0050	0.0150	0.0152	+1.4
3	3	0.0100	0.0150	0.0153	+2.0
3	3	0.0100	0.0200	0.0203	+2.0
3	3	0.0100	0.0100	0.0101	+1.0
3	3	0.0100	0.0000	0.0001	—
3	3	0.0150	0.0100	0.0103	+3.0
3	3	0.0150	0 0150	0.0153[b]	+2.0
3	3	0.0150	0.0200	0.0200	0
3	3	0.0150	0.0250	0.0254	+1.7
3	3	0.0200	0.0150	0.0153	+2.0
3	3	0.0200	0.0200	0.0202	+1.0
2	3	0.0200	0.0100	0.0102[c]	+2.0
2	3	0.0200	0.0150	0.0153	+2.0
3	2	0.0200	0.0200	0.0203	+1.5
3	2	0.0200	0.0250	0.0250	0

[a] Operator 1.
[b] Operator 2.
[c] Operator 3.

In a recent publication, Patton and Reeder (1956) reported on the use of a new indicator which they claim is superior to ammonium purpurate (murexide) in the presence of interfering ions. This indicator, 2-hydroxy-1-(-2-hydroxy-4-sulfo-1 naphthyl-azo)-3-naphoic acid is available from the Scientific Service Laboratories of Dallas, Texas. A prepared indicator mix, "Calver II," can be purchased from the Hach Chemical Co. of Ames, Iowa.

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SEPARATION OF CLAY MINERALS FROM CARBONATE ROCKS BY USING ACID[1]

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ABSTRACT

Various chemical methods of freeing the clay minerals that occur in limestones and dolomites have been used without regard to the effect the chemicals might have on the properties and structures of these clay minerals.

A procedure is here suggested that will accomplish the separation without significantly affecting the character of randomly interstratified illite-montmorillonite, chlorite, illite, or kaolinite, as shown by their X-ray diffraction diagrams.

The limestone or dolomite is treated at room temperature with acetic acid (less than 0.3 molar) or hydrochloric acid (0.11 molar). The weaker the acid concentration the greater the possibility that the clay minerals will be unchanged. Some carbonate rocks must be present throughout the period of acid treatment.

INTRODUCTION

Clay minerals that frequently occur in carbonate rocks in small quantities must be concentrated before they can be identified by the customary X-ray diffraction techniques. A physical method of clay mineral concentration would be most satisfactory, but physical processes are not always practical and frequently are even impossible. Techniques that employ chemicals to dissolve the more highly soluble carbonate portion are therefore in general use. Among the chemicals that have been used are certain inorganic and organic acids, most commonly hydrochloric and acetic acids.

Not only have acids with a wide range of pH been used for the removal of carbonates, but they have been employed at various temperatures. Few of the generally accepted techniques for chemically freeing the clay minerals from carbonate rocks have been evaluated with respect to their effect on the clay minerals.

This paper presents a preliminary investigation of physical methods of separating clay minerals from carbonate rocks, but, as these methods proved only partly satisfactory, the paper deals more fully with the development of a suitable procedure, using hydrochloric or acetic acid, that does not produce a change detectable by X-ray diffraction methods in those clay minerals commonly found in sedimentary rocks.

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METHODS OF SEPARATION

Physical

If the masses of clay in carbonate rocks are of such size that they can be removed by hand picking, no separation problem exists. However, disseminated fine clay particles can not be recovered by this procedure.

An attempt was made to effect a physical separation of clay minerals from two carbonate samples, one of dolomite and one of limestone, that were free from visible shale partings and had insoluble residue contents between 10 and 15 percent. The samples were crushed to minus 200-mesh sieve size. Two hundred gm of each was added to 250 ml of distilled water and mixed in a blender for 20 minutes. At the end of a 10-minute settling period, the suspended material in the blender was poured into a 1500 ml beaker and the liquid volume increased to 1000 ml by adding distilled water. This mixture was allowed to settle for 10 minutes, after which the upper 5 in. of liquid was siphoned off into a collecting beaker. The process was repeated until the 1500 ml collecting beaker was filled. After considerable washing and decanting and the use of filter candles to remove the excess water, the particles in the collecting beaker were dispersed. The material less than 2 μ in size was then removed

by sedimentation and analyzed by standard X-ray diffraction procedures employing settle slides.

The X-ray diffraction curves obtained from these slides showed only slight evidence of the presence of clay minerals. The clays manifested themselves in a broad, poorly defined reflection between 10 Å and 17 Å. The same samples treated with very dilute acetic acid (less than 0.17 molar [M] concentration) yielded distinct reflections from the basal planes of illite, chlorite, and a heterogeneous mixed-layer illite-montmorillonite assemblage. On the basis of these data it would seem that such a method of physical separation is likely to be of limited use for carbonate rocks in which the clay minerals are scarce, distributed homogeneously, and situated between the carbonate crystals.

Chemical

Introduction.—The following acids have been used to separate clay minerals from carbonate rocks: hydrochloric (Singewald and Reed, 1935; Grim, Lamar, and Bradley, 1937; Nutting, 1941; Robbins and Keller, 1952; Weaver, 1953; Gault and Weiler, 1955; Ray, Gault, and Dodd, 1957; Merrill and Winar, 1958; McAllister, 1958); acetic (Ray, Gault, and Dodd, 1957; Potter and Glass, 1958); formic (Ray, Gault, and Dodd, 1957); and sulphuric and oxalic (Nutting, 1941). Hydrochloric and acetic acids were selected for closer examination because they are common acids, form soluble compounds, and respectively show the effect of both strong and weak acid on clay minerals.

The effect of acid on clay minerals.—When dealing with clay minerals in carbonate rocks, the basic problem is one of effecting a separation of the two without damaging the clay minerals to the extent that the character of their initial X-ray diffraction diagrams are altered. Very little is known about the resistance of specific clay minerals to various acid treatments, but it generally is recognized that the nature of the acid, its concentration, the acid-to-clay ratio, temperature, duration of treatment, particle size, solubility, and crystallinity all influence the character of the acid-clay reaction.

Ray, Gault, and Dodd (1957) recognized hectorite as the clay mineral that "... reacts more rapidly with acids than other clay minerals." Nutting (1941), in a study of the action of dilute acids on clays of the montmorillonite group, observed "... silicates of the montmorillonite-beidellite group are much more easily attacked by dilute acids than those of the kaolin, mica, talc, or pyrophyllite groups."

Grim (1953) stated that when a clay mineral is acted upon by an acid "... it appears that the alkalies and alkaline earths are removed relatively more rapidly than the aluminum or iron, and that the iron is removed more rapidly than the aluminum. ... Acid attack begins around the edges of the particles and works inward. ... In the case of aluminum it appears that its removal is stepwise; i.e., it moves first from octahedral positions to exchange positions and then to complete solubility."

The fact that the alkalies and alkaline earths are the first to be removed from the clay lattice suggests that the acid attack begins around the edges of a crystal and works inward from the interlayer to the octahedral cations. For example, the gradual removal of interlayer potassium from muscovite results in a progressively more degraded product in which there is a corresponding decrease in the degree of crystallinity. Continued degradation produces expansible particles that become increasingly more abundant. Such a process is visualized as a progressive migration of degradation inward from the crystal edges and not as a wholesale simultaneous replacement of entire cation layers. As the degraded product is further attacked, the cations in octahedral coordination are removed to exchange positions and finally to free solution. As the clay is depleted of its alkalies, then of its magnesium and iron, and finally of its aluminum, the lattice is left with an increasing amount of void space and finally only the silica tetrahedral sheet remains.

SAMPLES STUDIED

The selection of clay minerals for investigation was based on their reactivity with acid and, with the exception of hectorite, on their widespread occurrence in sedimentary rocks. Hectorite, a montmorillonite, was included to gain a practical

TABLE 1.—*Source and location of the samples used to test the effect of acid treatment on clay minerals*

Sample Identification	Source	Location
Hectorite	W. Arthur White, Illinois State Geological Survey	Hector, California
Prochlorite	Herbert D. Glass, Illinois State Geological Survey	Val Malenco, Italy
Sedimentary chlorites		
Well crystallized	Maquoketa Shale, core No. 3323, depth 211′, Illinois State Geological Survey	$NE\frac{1}{4}$ $NE\frac{1}{4}$ $SE\frac{1}{4}$ sec. 26, T. 41 N., R. 11 E., Cook County, Illinois
Poorly crystallized	Maquoketa Shale, outcrop in valley wall	$SE\frac{1}{4}$ $NE\frac{1}{4}$ $SW\frac{1}{4}$ sec. 17, T. 11 S., R. 2 W., Calhoun County, Illinois
Pennsylvanian age limestone	Operating quarry	$SW\frac{1}{4}$ $SE\frac{1}{4}$ $SE\frac{1}{4}$ sec. 4, T. 9 N., R. 14 W., Clark County, Illinois
Pennsylvanian age shale	Operating quarry 15 in. layer in limestone listed above	$SW\frac{1}{4}$ $SE\frac{1}{4}$ $SE\frac{1}{4}$ sec. 4, T. 9 N., R. 14 W., Clark County, Illinois

working knowledge of clay mineral sensitivity to hydrochloric and acetic acids based on work previously done (Ray, Gault, and Dodd, 1957). Samples containing chlorite and illite were used to check the effect of acid treatment on clay minerals exhibiting varying degrees of crystallinity. Limestone and shale samples of Pennsylvanian age were selected to show what effects acid treatment might have on any of the clay mineral components contained in them, but specifically on the mixed-layer phases. A list of the samples used is given in table 1.

EFFECT OF ACIDS ON SAMPLES

Hectorite (Montmorillonite)

A sample of sodium-saturated hectorite (pH 9.8) containing a small amount of calcite was treated over a period of 48 hours with acetic acid solution of 0.17, 0.33, 0.50, 0.83, 1.33, 6.66, and 10 molar (M) concentration and with hydrochloric acid solutions of 0.10, 0.21, 0.31, and 0.51 M concentration. Forty gm of the original sample were crushed to pass a 20-mesh sieve and mixed in a blender for 30 minutes with 400 ml of distilled water. Fifty ml portions of the less than 2-μ fraction were mixed with 200 ml of acid solution of the concentrations indicated above and allowed to digest for 48 hours. At the end of this period the mixtures were diluted with distilled water to 1000 ml volume and repeatedly washed and filtered (using porcelain filter candles on vacuum) until the clay was dispersed. The volume of each mixture was then reduced to 20 ml. Settle slides were prepared from these mixtures for X-ray diffraction analysis.

After treatment with the weakest acids, calcite was not detected on the X-ray diffraction curve. The prominent first, third, and fifth order basal 00l reflections for natural hectorite (15.5 Å, 5.14 Å, 3.09 Å) showed a progressive broadening and flattening as the concentration of the acid used in treatment was increased. The second and fourth order reflections were very weak but behaved in a similar manner, finally disappearing completely. This change is only barely detectable with a 0.33M solution of acetic acid or a 0.21M solution of hydrochloric acid. As the concentration is increased, the effect becomes more noticeable. Acetic acid solutions greater than 1.33M concentration only slightly increased this effect. In addition, there was a corresponding slight but progressive shifting of the position of maximum intensity of these reflections to lower angles. The samples all showed an 00l series of X-ray reflections for about 17.5 Å after treatment with ethylene glycol. It is suggested from these data that the interlayer cations were being stripped from the clay and that the clay was becoming more freely expansible as the acid con-

centration was increased. The situation is further complicated by availability of calcium ions from dissolved calcite and of magnesium and aluminum ions released from octahedral coordination at crystal edges (Kerr and others, 1956) or interlayer positions of hectorite. These ions, together with hydrogen, may replace the interlayer sodium to varying degrees, resulting in further irregularities in the character of X-ray diffraction data, the sum of which is increased broadening and flattening of the 001 basal reflection.

Chlorite

The effect of acid solutions of various concentrations on a clay mineral exhibiting variable crystalline character was examined by using a well crystallized metamorphic chlorite (prochlorite) and samples of chlorite collected from weathered and unweathered sedimentary rock sources (see table 1). The chlorite in both sedimentary rock samples is considered to be the ortho variety, which commonly contains magnesium and aluminum as cations in the brucite layer and very little iron. As the degree of crystallinity decreases the 001/002 ratio increases. The prochlorite, which is an orthochlorite (Dana and Ford, 1950), has a ratio of slightly less than 0.5. The well crystallized sedimentary chlorite has a slightly higher ratio of approximately 0.75, whereas the poorly crystallized chlorite has a nearly reverse ratio of 2.

The prochlorite was treated with acetic acid solutions of different concentrations to test the resistance of well crystallized chloritic materials to such treatment. The sample was examined untreated, glycol-saturated, after heat treatment at 440° C and 550° C for slightly more than one hour, and after being treated with 500 ml of 5M and 10M concentration acetic acid solutions for 84 hours. Acid treatment had no apparent effect on this chlorite. Heating had no apparent effect on the mineral after treatment at 440° C, but following treatment at 550° C almost complete diminution of all but the first order reflection occurred; the first order reflection was considerably accentuated.

The well crystallized sedimentary chlorite was unaffected after treatment with acetic acid solutions of varying strength up to 10M concentration for a period of 84 hours. After being heated at 450° C for one hour, the first order reflection was unaffected while all others were attenuated; the third order reflection disappeared completely. Heating at 575° C for one hour destroyed all but the second and first order reflections, both of which shifted by about 0.4 2θ toward higher angles. Glycol treatment of the acid- and heat-treated samples had no effect on the 14 Å first order reflection. The decrease of d-spacings is considered to be caused by the collapse of particular layers to thicknesses approximating 10 Å because of initial deficiencies in the brucite layer (Bradley, 1953).

As the strength of the acid solution used to treat poorly crystallized chlorite is increased, the first order 14 Å reflection broadens and the third order reflection decreases in intensity. Such broadening is distinct with acetic acid solutions of concentrations as low as 1 molar. Diffraction curves of these samples, glycol-saturated, indicate that the amount of 14 Å component decreases during acid reaction. When the sample was heated at 440° C for one hour, a moderately prominent, broad peak appeared at 13.6 Å with a very low, but sharp, second order reflection. After heating at 550° C for one hour, a broad hump appeared between 14.2 Å and 11.3 Å with no second order reflection. Comparison between these two curves indicates that this chlorite is poorly crystallized. Heat treatment resulted in collapse between particular layers because of deficiencies in the brucite layers. Glycol saturation of the sample that was heated at 550° C produced no significant change in the diffraction trace, suggesting that the material represented by the prominent, broad maximum at 14.2 Å/11.3 Å consists of a homogeneous random mixed-layer assemblage of 10 Å and 14 Å components.

That (1) acid reacted with the poorly crystallized chlorite and not the well crystallized chlorite, and (2) the former is noticeably affected by heat treatment suggest that poorly crystallized chlorite possesses the greater number of deficiencies in the brucite layer. The less well crystallized material is most susceptible to reaction with acid.

Illite

Illite, present in the samples of Maquoketa Shale, contains few or no expansible layers and is not detectably affected by treatment with solutions of acetic acid (10M) and hydrochloric acid (3.7M) over a period of 84 hours. The samples of Pennsylvanian age limestone contain an illite of similar character that did not react with a 16.6M solution of acetic acid or a 10M solution of hydrochloric acid plus a homogeneous mixed-layer assemblage of expansible and nonexpansible 10 Å layers.

The mixed assemblage is noticeably affected by treatment with 0.8M acetic and 1.37 M hydrochloric acid solutions over a 72-hour period. With higher acid concentrations the effect on this component becomes more pronounced and manifests itself as a change from a mixture composed predominantly of 10 Å layers to a heterogeneous mixture of particles, the interlayer distances of which show considerable variation greater than 10 Å. Prolonged treatment of the mixture with acid produces a more pronounced shift to larger d-spacings. Treatment with an acetic acid solution of 1.65M concentration for 72 hours destroyed the homogeneity of the mixture. After treatment of this material with excess 2N solution of potassium chloride for 48 hours, followed by 10 washings with distilled water and intervening mixing in a blender, the geometry of the initial diffraction pattern was regained. The effect of acid treatment was a disturbance of the organization of the interlayer water molecules by the stripping out of potassium, thus reducing the degree of homogeneity by increasing the number of more freely expansible layers. Saturation with potassium returned the mixture to its initial state. Treatment of mixed-layer expansible and nonexpansible assemblages with at least 0.8M acetic or 1.3M hydrochloric acid solution detectably alters the expansible particles by stripping out the potassium ions and allowing additional layers to become more freely expansible.

The mixture was more severely affected by treatment with a 1.3M solution of hydrochloric acid after all carbonate had been dissolved than it was when the carbonate was still present. This suggests that carbonate serves as a "protecting" agent. When acid is added in the presence of carbonate it expends itself more rapidly on the carbonate than on the clay, resulting in an abrupt increase in pH. Continuation of this process increases the clay-to-carbonate ratio. When sufficient clay has been released it can be removed by decantation. Small amounts of carbonate in the less than 2-μ fraction were not found to be in any way detrimental to diffraction analysis.

Samples of clay collected from a Pennsylvanian age shale and containing a large amount of homogeneous random mixed-layer illite-montmorillonite were used to investigate the importance of exposure time and acid-to-clay ratio. Samples were prepared so that the ratio of acid solution to the less than 2-μ clay material was approximately 200-to-1. Acetic acid solutions of 0.8M and 3.3M concentration and hydrochloric acid solutions of 0.36M and 1.3M concentration were used to treat the shale for periods of 1, 4, 8, and 16 days. The lowest concentrations of either acid solution had no detectable effect on the clay. The 3.3M concentration of acetic acid and the 1.3M concentration of hydrochloric acid over a period of 24 hours produced significant effects. These included a decrease in the degree of homogeneity and an increase in the ratio of expansible to nonexpansible layers caused by the stripping out of interlayer potassium ions. These effects became more pronounced as the exposure time and acid strength increased.

Kaolinite

Kaolinite occurs in both samples of Pennsylvanian rocks. It was detectably unaffected after treatment with 16.6M solutions of acetic acid or 10M solutions of hydrochloric acid over a period of 72 hours.

SUMMARY

When clay minerals are treated with acid, caution must be exercised because individual clay minerals react differently to acid treatment. The effect of acid treatment on particular clay minerals is outlined briefly below:

1. Hectorite (*montmorillonite*). An acetic acid solution of 0.33M concentration or a

hydrochloric acid solution of 0.19M concentration are sufficient to produce a slight change in the character of the X-ray diffraction data for hectorite. This change becomes more pronounced with increasing acid concentration and manifests itself on the X-ray diffraction curve as a broadening and flattening of the 001 series of basal reflections and an attendant shift to lower angles.

2. Chlorite. Well crystallized chlorite is unaffected by 16.6M acetic or 10M hydrochloric acid solutions over a period of 72 hours. As the degree of crystallinity decreases, or the number of deficiencies in the brucite layer increases, the acid-susceptibility increases. A poorly crystallized chlorite is affected by a 0.8M concentration of acetic acid or a 1.3M concentration of hydrochloric acid, whereas 0.17M (acetic) or 0.36M (hydrochloric) concentrations produce no detectable effect.

3. Illite and Mixed-Layer Assemblages. Well crystallized illite is not affected by acetic or hydrochloric acid solutions of 16.6M or 10M concentration, respectively. As the number of expansible layers increases, or as the amount of interlayer potassium ions decreases, the clay becomes more susceptible to acid reaction. A 0.8M solution of acetic acid or a 1.9M solution of hydrochloric acid is sufficient to affect the diffraction data obtained from mixed-layer nonexpansible and expansible illite-montmorillonite. No detectable effect was produced on this clay by a 0.17M concentration of acetic acid or a 0.36M concentration of hydrochloric acid.

4. Kaolinite. Well crystallized kaolinite was unaffected after treatment with 16.6M or 10M solutions of acetic and hydrochloric acid, respectively, over a period of 72 hours.

5. General. Expansible minerals, or those with expansible constituents, are the most susceptible to acid reaction. No reaction was apparent from X-ray diffraction curves between nonexpansible clay minerals and acetic acid solutions of 16.6M and hydrochloric acid solutions of 10M concentrations for 72 hours.

RECOMMENDED LABORATORY PROCEDURE FOR SEPARATION OF CLAY MINERALS FROM CARBONATE ROCKS

A laboratory procedure for the separation of clay minerals from carbonate rocks, utilizing weak hydrochloric or acetic acid, is described below. It is believed that by this process clay minerals can be freed from carbonate rocks without significant changes in the minerals.

A sample of approximately 150 gm is washed and scrubbed in distilled water to remove possible adhering clay; the sample is allowed to dry. It is then crushed to pass a 60-mesh sieve. A small amount of the crushed material (less than 10 gm) is placed in 100 ml of 0.5M acetic acid. If there is no reaction, the sample probably is mainly dolomite in which case the procedure for dolomite mentioned below is followed. If there is reaction, the procedure for limestone is followed even though the sample may be dolomitic.

If there is a reaction the unused minus 60-mesh material is mixed with 100 ml of distilled water in a 1500 ml beaker. To this is added 1 liter of acetic acid of less than 0.3M concentration. The mixture is stirred periodically until the reaction ceases, a period generally requiring one to several days. The impotent liquid is then separated from the solid residue by filtering or decanting. Additional acid is added and the process repeated until $\frac{1}{8}$ to $\frac{1}{4}$ of an inch of very fine dark-colored material covers the undissolved limestone after settling. This material includes the clay and other insolubles from the limestone.

It is important in the foregoing steps that some undissolved limestone be present at all times as this helps to prevent alteration of the characteristics of the clay.

When an adequate accumulation of insoluble residue has formed, the clay is separated from the residue and the undissolved limestone by mixing the solids with 300 ml of distilled water and, after a two minute settling period, decanting the mixture into a 1500 ml collecting beaker. This is repeated until the liquid decanted is essentially clear. The solids in the 1500 ml beaker are washed by decanting or filtering off the supernatant liquid until the fine-grained solids are thoroughly dispersed. The suspension is allowed to settle for 2 hours before oriented aggregates of the less than 2-μ clay mineral fraction are prepared (Bradley, Clark, and Grim, 1937). An eye dropper is

used to transfer the dispersed clay to glass slides.

If the sample is indicated by lack of reaction to the preliminary acetic acid test to be dolomite, the procedures mentioned above are followed except that a hydrochloric acid solution of less than 0.11 molar concentration is used.

It should be noted that the weaker the acid used to cause the separation of carbonate and clays, the greater will be the likelihood that the clay will be unaffected.

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NOTES

RAPID DETERMINATION OF CALCITE-DOLOMITE RATIOS IN SEDIMENTARY ROCKS[1]

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X-ray diffraction techniques permit rapid measurement of calcite-dolomite ratios in sedimentary rocks with a standard deviation of 1.3 percent and a detection limit of about 5 percent.

From a large sample of powdered and homogenized rock, about 1 gm is extracted for further pulverization. Greatest reproducibility is obtained by mounting the powder with thermo-setting plastic or Canada balsam on standard 45×26 mm glass slides so that the pasty mixture is 1 to 2 mm thick over the slide. After setting, a light grinding with abrasive on plate glass produces a smooth flat surface and eliminates any preferred orientation which might develop at the surface.

The strongest X-ray diffraction spectra of calcite and dolomite are used. These correspond to d spacings of 3.035 Å and 2.880 Å which, with CuK_α radiation, are recorded at 2θ angles of 29.35° and 30.8° respectively. The intensity peaks are close together, permitting one continuous run from about 29° to 31° using the flat region around 30.0° as background. The integrated intensities of diffraction of standard samples are determined either by summation of gamma counts over the angular extent of the curves, with a correction for the background, or by planimeter measurement of the area under diffraction curves as drawn by the recorder.

A calibration curve, incorporating all of the preparatory, instrumental, and measuring errors, is drawn giving the relation between relative weights of calcite and dolomite and the relative integrated intensities of diffraction.

Natural variation in the composition of the two minerals has no measurable effect. Pink (Mn), brown (Fe), and white dolomites mixed in various combinations with several calcites gave diffraction intensities equally proportional to amounts. Peak heights of diffraction curves instead of areas may be employed with some loss of precision. Twelve replicate determinations of one sample, which was remounted in the goniometer 12 times, showed a range about the mean value over one and one-half times greater for peak height measurements than for area measurements. Wide X-ray transmission slits expose a greater area of the sample material to radiation but produce only a very slight increase in precision, probably as a result of the broader curves which facilitate planimeter determinations of the area.

Measurements are free of any interference from sulphides such as pyrite, marcasite, galena, and sphalerite and from other minerals which might occur in the rocks, such as quartz, rhodochrosite, magnetite, aragonite, siderite, smithsonite, celestite, barite, hematite, goethite, halite, and the clay minerals. Samples with considerable amounts of albite, gypsum, and polyhalite, however, might be expected to develop interfering reflections. The strong diffraction spectra chosen are relatively insensitive to stacking fault variables, such as in protodolomite.

Using a Philips X-ray machine with a type 42202 goniometer and a scanning rate of $\frac{1}{8}$° per minute, a plot of weight percent dolomite (y) against $\text{area}_{dol}/\text{area}_{dol}+\text{area}_{cal}$ (x) for a series of natural standards comprising various combinations of dolomites and calcites, gave a linear relationship:

$$y=95.3x+5.52.$$

One sample was analyzed 12 times and precision was evaluated according to a method by Shaw and Bankier (1954). The standard

[1] Manuscript received April 8, 1960.

deviation, s_x, obtained when analyzing any given sample once is 1.84; duplicate analysis reduces s_x to 1.30; triplicate to 1.06. Thus with triplicate analysis, there is a 68 percent probability that the true value (weight-percent dolomite) lies between $y \pm 1.06$ percent of the value y obtained. By choosing suitable scale factors in the counting circuit, about 5 percent is the least amount of either mineral which can be detected.

The technique is especially valuable in fine-grained limestones or dolostones where the small size of the individual crystals precludes staining methods.

The authors gratefully acknowledge generous monetary grants from Imperial Oil Limited to aid in a study of trace elements in dolostones.

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THIN SECTIONS OF CLAY AND SHALE[1]

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Thin sections of clay and shale are not often studied in geologic investigations because it is difficult to make standard size sections of such soft rocks. Impregnation techniques useful for porous rocks are not easily applied to shale because of its very low permeability, which permits little if any saturation by the viscous impregnating media and because some kinds of clay and shale, even air dried, contain too much water to withstand the temperatures used in impregnation and mounting of the specimens. Despite these difficulties, many excellent thin sections of clay and shale have been made. Ross and Hendricks (1945) and Grim (1933), among others, have shown how much can be learned from petrographic study of clays even though X-ray analysis may have largely replaced petrographic methods of identification of clay minerals.

The purpose of this note is (1) to call attention to a method of impregnating moist samples of shale developed by Mitchell (1956) which makes the preparation of thin sections of these rocks largely a routine matter; (2) to describe methods of sampling that make it easier to prepare thin sections of most kinds of clay; and (3) to describe useful techniques in sectioning dried samples.

Mitchell was concerned chiefly with the relation of the fabric of clays to their engineering properties. Because the effect of drying on fabric was unknown, he used samples that contained their natural moisture. The impregnating medium he used was a wax-like high molecular weight polyethylene glycol compound (Carbowax 6000, produced by the Carbide and Carbon Chemical Co.), which is soluble in water in all proportions and melts at approximately 55° C. The clay sample is soaked for three days in the melted wax at a temperature of approximately 60° C.

The sample is impregnated by the diffusion of the wax through the moisture content of the sample. After impregnation, the thin section slice must be sawed and ground in kerosene. A petroleum solvent should be used to remove kerosene from the slice before mounting it on a glass slide and before cementing the cover glass on the finished slide. The cement should be an air-setting plastic that does not require heat.

The chief disadvantage of the impregnating wax medium is that it is not isotropic. The birefringence of the wax seems to vary from slide to slide, but it has second-order yellow and red interference colors in most sections of standard thickness. The wax crystallizes in feathery aggregates. These characteristics make uncertain the study of minute grains such as may be found in the interior of Foraminifera or in other cavities in the rock, but they do not interfere with

[1] Publication authorized by the Director, U. S. Geological Survey. Manuscript received April 8, 1960.

studies of grains larger than approximately 50 microns or with studies of the orientation of clay minerals.

The wax reacts with pure montmorillonite in bentonite so that the resulting thin section is not very useful. No reaction has been detected, however, in rocks that contain as much as 50 percent montmorillonite associated with other clay minerals.

If special methods of collecting are used by the geologist in the field, most soft impervious rocks can be sectioned easily by use of Mitchell's technique and many by slight modifications of ordinary techniques.

The outcrop is dug into until firm pieces the size of a hen's egg can be obtained. The depth to which digging is necessary will range from 1 to 3 ft but will nearly always reach the zone in which the rocks contain considerable moisture. It is desirable to take several samples. The pieces should be wrapped immediately with several separate layers of aluminum foil, which protects the sample and preserves much of the moisture content. If absolute retention of the moisture content is desired, the sample can be wrapped first in one of the plastic food wraps, and then in at least two layers of aluminum foil. The major cause of fragmentation in the weathering of many clayey rocks seems to be the rapid loss of moisture, which is avoided by the above technique. The layers of foil are not absolutely air tight and moisture is lost from the sample very slowly. When unpacked in the laboratory, many samples will be completely dry but not broken into fragments, whereas the same material, after exposure in the field, would have gone to pieces in the time necessary to describe the unit from which the sample was taken.

Samples retaining their moisture content can be impregnated with the polyethylene glycol. Samples that have dried slowly while wrapped in aluminum foil, however, can be handled almost like ordinary rock. They can be sawed on a dry bonded-carborundum saw, or on a regular diamond saw if kerosene is used as the lubricating fluid. The sawed surface is prepared for mounting on the slide by grinding in kerosene with a more fluid slurry than is used for grinding harder rocks; less pressure is used on the lap or glass plate to avoid the tendency of the abrasive to become embedded in the rock. If the slice seems likely to break up after sawing, it can be dipped quickly in a melted resin to provide a bonding coat that will hold the specimen together.

If the sample contains relatively hard grains embedded in a clay matrix, such as the feldspar grains commonly found in the lower part of a bentonite bed, the rock slice can be impregnated under vacuum by one of the isotropic plastics available as an aerosol spray. A dish of aluminum foil shaped to the contours of the specimen is convenient to use. The spray of the plastic is directed into the dish and the plastic quickly accumulates as a liquid with low viscosity that hardens slowly enough for good impregnation to take place while under vacuum. After the first flat surface is ground on the impregnated slice, it may be advisable to spray the surface until no more plastic is absorbed, and then regrind the surface. Before spraying the specimen, kerosene should be removed by washing the specimen in a petroleum solvent as a "degreaser." After final grinding the specimen is mounted on the slide without the use of heat. Diamond saws running in kerosene make somewhat smoother cuts than dry saws in trimming the butt of the specimen from the slide.

Some kinds of bentonite change color after contact with kerosene but petrographic study is not hindered.

ACKNOWLEDGMENT

Nathaniel S. Taylor, U. S. Geological Survey, Denver, Colorado, assisted in developing the methods applied to air-dried samples and has shown great skill in applying these methods, as well as wax impregnation, to a wide range of materials.

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REVIEWS

Beaches and Coasts, by Cuchlaine A. M. King, 1960. Pp. xii+403, 157 figs.; 6×9 in.; cloth. Edward Arnold Ltd., London, Price $14.50.

This completely new book is billed (on the dust jacket; by inference) as the successor to D. W. Johnson's Shore Processes and Shoreline Development, of 1919. The author points out, in the preface, that several other recent books have treated the same subject (Shepard; Steers; Guilcher). The present work is justified as a different treatment, and "is an attempt to gather together some of the recent work on coastal problems, especially those associated with the character of the beach." No other aim is stated.

Chapter headings (and some of the subdivisions) are as follows: I. The main factors on which the character of the beach depends (beach material; waves; tides; winds) (35 pages). II. Methods of research (15 pages). III. Waves (deep water; generation; refraction; shallow water) (67 pages). IV. Movement of material on the beach (normal to the shore; longshore; grading; sorting) (58 pages). V. Beach profiles (experimental results; beach surveys) (28 pages). VI. Effect of wind (model experiments; observations in nature; coastal dunes) (20 pages). VII. Classification of beaches and coasts (20 pages). VIII. Constructive wave action and coastal accretion (32 pages). IX. Destructive wave action and coastal erosion (42 pages). X. Beach gradient and beach profiles (35 pages). XI. Historical data on coastal change (10 pages). XII. Coastal types and their development—the marine cycle (23 pages).

A reading of these headings shows that this book is much less broad in scope than either Shepard or Guilcher.

Organization-wise, a novel feature is the placement of summaries at more-or-less regular intervals throughout the chapters. These summaries are easy to find because of the bold-face subtitles which are used to identify them. A single, rather detailed, index includes both subject matter and personal names. References at the ends of the several chapters are arranged neither alphabetically nor chronologically, but rather in the order in which the citations are made in the text.

The discussions of waves, tides, and the amphidromic effect, although scattered through several chapters, are simple, direct and easy to follow. A student with no background beyond elementary algebra should be able to handle this material easily. Obviously it is not a highly sophisticated approach, but it is adequate. The discussion of waves is rather complete for a book of this nature, including many charts which are useful in wave forecasting or hindcasting, and in relating various pertinent parameters.

The treatment of beach and near-shore sediments is quite elementary, but sufficiently detailed for the purposes of the book.

The classification of beaches is based on a subdivision into (1) shingle beaches, and (2) sand beaches. Further splitting is done on the basis of tidal or tideless reaches.

The chapter on coastal classification includes the schemes of Suess, D. W. Johnson, F. P. Shepard, C. A. Cotton, and H. Valentin. Although none of those is accepted wholeheartedly by Dr. King, Valentin's advance-retreat dichotomy is considered better than the others. A detailed treatment of the advantages and disadvantages of each is undertaken. No mention is made, however, of the energy concepts of, for example, Armstrong Price (see Tanner, 1960).

In the actual business of organizing the text starting on page 253, the author adopts the following coastal classification:

I. Constructive coasts.
  A. Straightened by marine deposition.
  B. Made irregular by marine deposition.
  C. Salt marshes.
II. Destructive coasts.

Beginning on page 366, organization of the text follows this simple scheme:

I. Steep indented coasts.
II. Steep straight coasts.
III. Flat indented coasts.
IV. Flat straight coasts.

An English-French-German-Dutch-Swedish glossary of selected terms, dealing with the beach, appears on page 50.

Several criticisms can be stated. The grammar is rather "rough." Sentences are incomplete, where it would have been easy to have made them complete. Many statements are unusually involved, even though short. Fortunately this type of thing occurs where the text is not closely reasoned, but is nevertheless annoying.

On page 3 one might infer that Inman invented the phi notation. On page 4, the definition of "dilatancy" is skirted, and the term is used, instead, in a sentence which is certainly no definition, and is probably misleading. Armstrong Price's name is given, at least twice, as W. Armstrong-Price, and is listed (logically enough) in the index under the A's. On page 38, one finds the expression "medium" diameter; should this be "median?" On page 95 the author writes "... orthogonals ... are drawn everywhere parallel to the wave crests ..."; should this be "perpendicular?"

The use of dimensional analysis is introduced (page 38) in such a way that the reader will think it pertinent to beach studes (as it is); the technique is not discussed, however, and no obvious references are listed. It is the reviewer's opinion that, in general, neither geologists nor mathematicians, in the United States, are familiar with the subject, and therefore adequate sources should have been included (i.e., Duncan, 1953; Focken, 1953; Langhaar, 1954; Giles, 1956; Rouse, 1959).

On page 138, the statement is made that where beach materials are relatively coarse, more movement can be noted. One would perhaps infer that more movement means higher energy levels, and that this in turn would mean coarser materials. On page 247, however, Dr. King explains that coarse materials are more mobile than fine!

Although this partial list of unhappy statements and phrases may appear long, the reviewer's general impression is that this is a fairly good elementary college-level book, which will be greatly improved when it is more carefully edited for a future revision.

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Spiral motion of fluids, by Václav Kolář. 1956. Pp. 118, 54 figs.; 6.5×9.5 in.; paper. Rozpravy, Československé Akademie Věd, Ročník 66 Sešit 5, Prague. In Czechoslovakian, with cutlines and summaries in Russian and English.

The relationship between helicoidal flow, river meandering, and sediment transportation, is not yet clear. It has been said, commonly, that transport of bed load is responsible for meandering. In this type of analysis spiral flow has no important place. On the other hand, sediment-free streams are known to meander: for example, model streams (Tanner, 1960), super-glacial meltwater streams (Leopold and Wolman, 1960), the jet stream in the atmosphere and the Gulf stream in the Atlantic ocean (Riehl et al., 1954). Obviously bed-load transport does not explain meandering.

The article by Kolář reports the results of a model study which was dimensionally correct except for the possible effects of temperature gradient. The model stream was run through a straight channel with fixed walls, so meandering was not possible. Helicoidal flow was studied in detail, and shown in a number of clear photographs. The results do not support any particular set of ideas about spiral flow and stream meandering, but do contribute a great deal of new information about the spiral phenomenon itself and therefore stream behavior in general.

Kolář reports that spiral flow appears in stream reaches where there is curvature, an obstacle, or a sudden change in discharge. He attributes both river bank erosion, and channel surface cavitation to this mechanism.

Where a stream is wide and shallow, a main (or first order) spiral may induce second order spirals on either side. The second order features are left-handed where the first order flow is right-handed, and vice versa. This produces alternate bands of ascending and descending currents, oriented parallel with the stream banks. Third and higher order spirals have been observed only rarely. Hugh Casey (1935) is quoted as having produced 14 parallel spirals which eroded seven longitudinal furrows, of the same width, in the channel bottom. The experimental flume was 15.75 inches wide, slope of 0.0025, and water 1.13 inches deep. These furrows, and their associated ridges, should look much like ripple marks, except that the crests would be parallel with the average flow direction.

The character of spiral flow is attributed by Kolář to (1) velocity distribution at the beginning of the reach, (2) degree of curvature, (3) hydraulic radius, and (4) ratio of curvature radius to a representative length such as width. Cross circulation is related to super-elevation on the free surface next to the concave bank. Reversal of the sense of circulation (i.e., from left-handed to right-handed) is described, but not explained.

Dimensional analysis of the problem yielded, finally, four dimensionless parameters which guided model planning: an angle of deflection, the ratio of spiral reach to water depth, the Reynolds criterion, and the Froude number. The Reynolds number was kept essentially constant between 15,500 and 16,000, and the Froude number constant at 0.03.

The spiral reach (distance from inception to total decay) varied between 32 and 70 times the water depth, with the smaller limit being approached as the deflection angle was brought close to one degree. Beyond a distance = 70d, all spiral flow had decayed; however, Kolář used fixed walls in his experiments, and therefore could not state what would happen if the walls were free to move easily in response to the action of the helix (as is the case in alluvial rivers).

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Microscopic Sedimentary Petrography, by Albert V. Carozzi, 1960. Pp. vi+485, 88 figs., 6×9 in., cloth. John Wiley and Sons, Inc., New York. Price, trade edition, $11.50.

Carozzi's useful compendium describing sedimentary rocks as seen in thin section would be more aptly entitled a monograph on diagenesis. The title might lead one to suppose that the optical properties of minerals and varieties peculiar to sediments would be included, whereas the author presupposes the reader's working knowledge of the polarizing microscope and concentrates on the textural relationships displayed by the minerals.

Sedimentary rocks are arranged in three major groups: clastic rocks (including arenaceous-, rudaceous-, pyroclastic-, and argillaceous types), biochemical rocks (including carbonate-, siliceous-, iron-bearing-, and phosphatic types), and chemical rocks (evaporites). Discussion of each kind and variety of rock proceeds largely on the basis of the mineralogic and textural changes produced during diagenesis (and for a few varieties only, during metamorphism).

The book includes excellent bibliographies that are particularly valuable to the average American reader for their thorough coverage of the European literature—a field commonly not given its due in this country.

Geologically-minded readers may well express surprise at the procedure used by the author in abstracting the work of others. The emphasis is on certain general or "ideal" mineralogic associations that recur repeat-

edly in various localities and in rocks of different ages; detailed descriptions that may be of only local significance are omitted. By ignoring the local setting the author has indeed succeeded in emphasizing the mineralogic assemblages. The success of this approach is somewhat mixed, however, for mineralogic details that are controlled by local provenance (the kind of quartz grains, for example) are generally treated in the same manner as the mineralogic and textural details that contribute to the "ideal" types. The reviewer, for one, would prefer to generalize ideal rock types from a series of specific examples complete with local settings.

American readers will also welcome the author's different approach to sandstone petrography. Though they may lament the complete absence of any discussion of the provenance significance of the clastics themselves, they are at least spared the rampant rigid, almost Neo-Wernerian, philosophy which insists that grains of a particular mineralogic composition are always deposited with identical textural characteristics under unfailingly similar tectonic settings. Another useful feature is the emphasis given to the petrography of phosphatic, iron-bearing-, and evaporitic rocks—the "poor relations" in most American sedimentary petrographic literature.

The illustrations are excellent, and the photomicrographs, especially, are extremely well reproduced and exceedingly clear. Only one illustration (fig. 49, a line drawing related to oölites) is original with the author, however, a surprise in view of the author's own distinguished career as a sedimentary petrographer.

This book represents a vast and valuable compilation of the descriptive mineralogy of the major kinds of sedimentary deposits; it should be on the shelf of every student who is concerned with the mineralogy of sedimentary rocks.

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